NASA's Exoplanet Technology Needs

NASA Tech Days 2012
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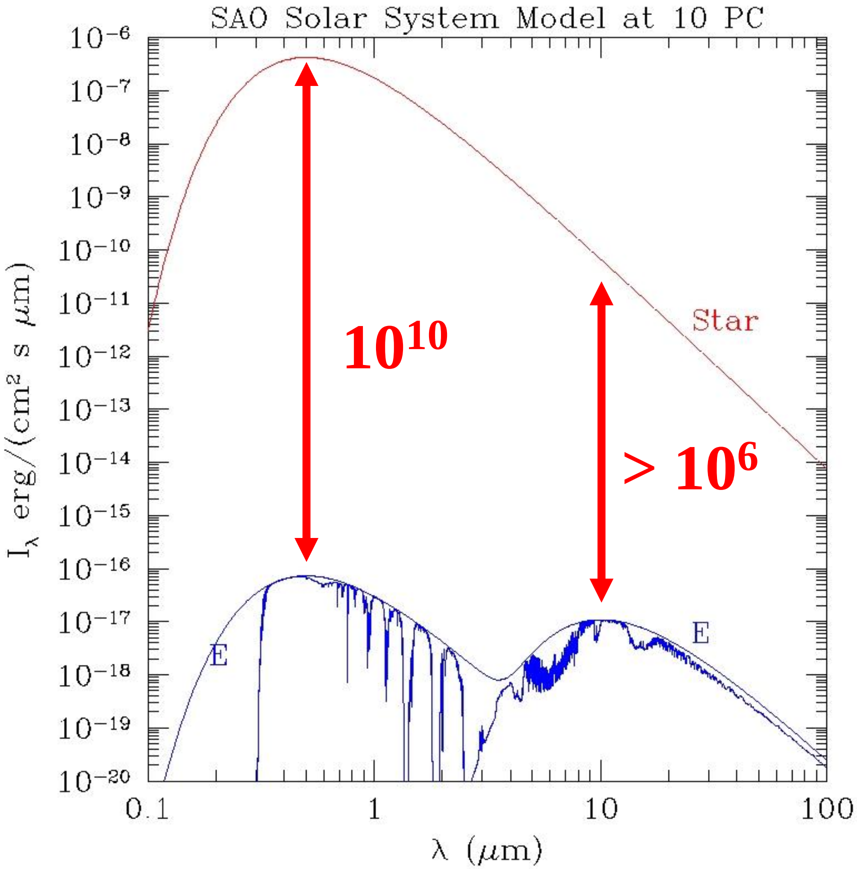
Why it's hard to see them

- The planet is 10^{-10} times dimmer than the star.
- A star 20 parsec (66 ly) away, with a planet 1 AU from the star: the angular separation is 0.05 arcsecond.
- Using a 10m telescope, operating at λ=600 nm, the star / planet angular separation would be 4 λ/D (4^{th} Airy ring).

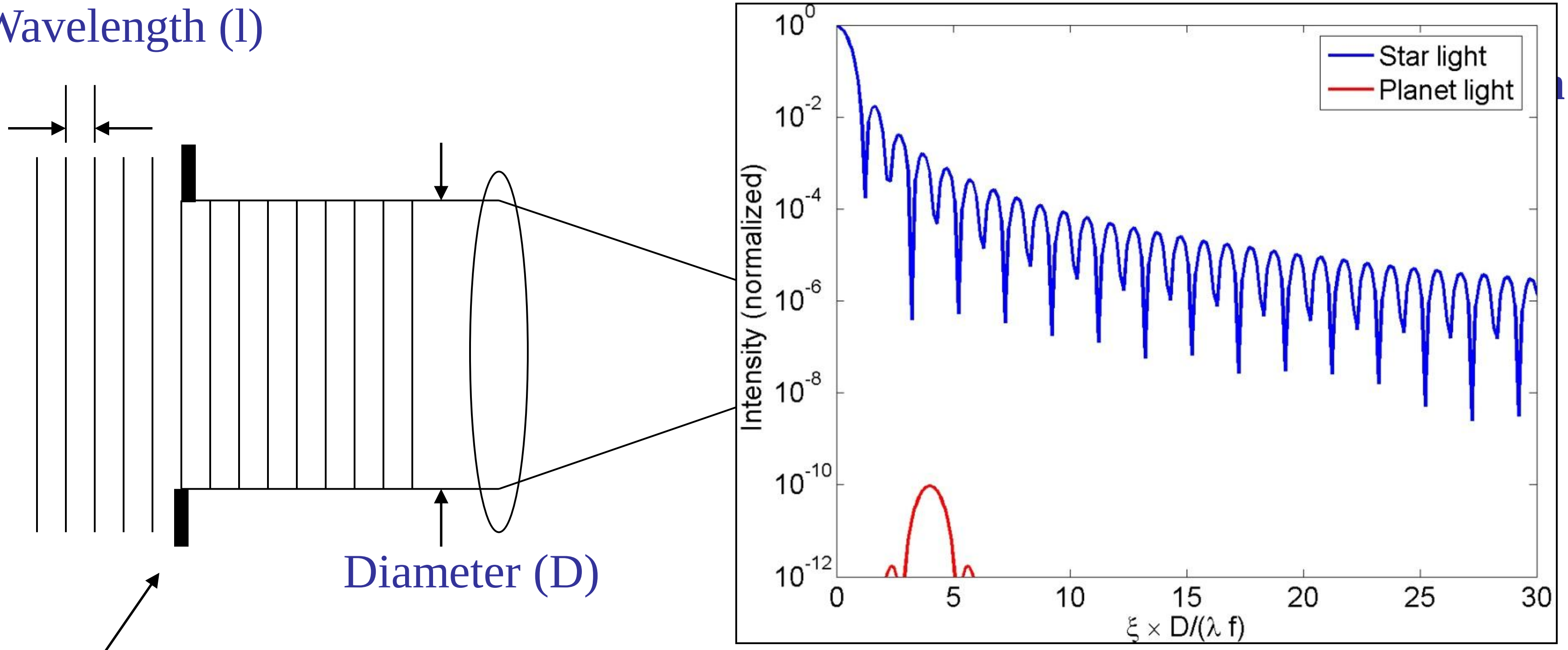
Model spectrum of the Sun and Earth as seen from a distant star



The Diffraction Problem

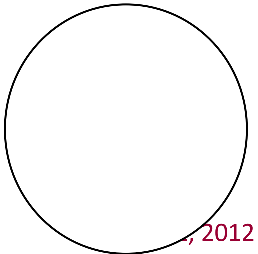
Unfortunately, the planet would be

Wavelength (l)



Diameter (D)

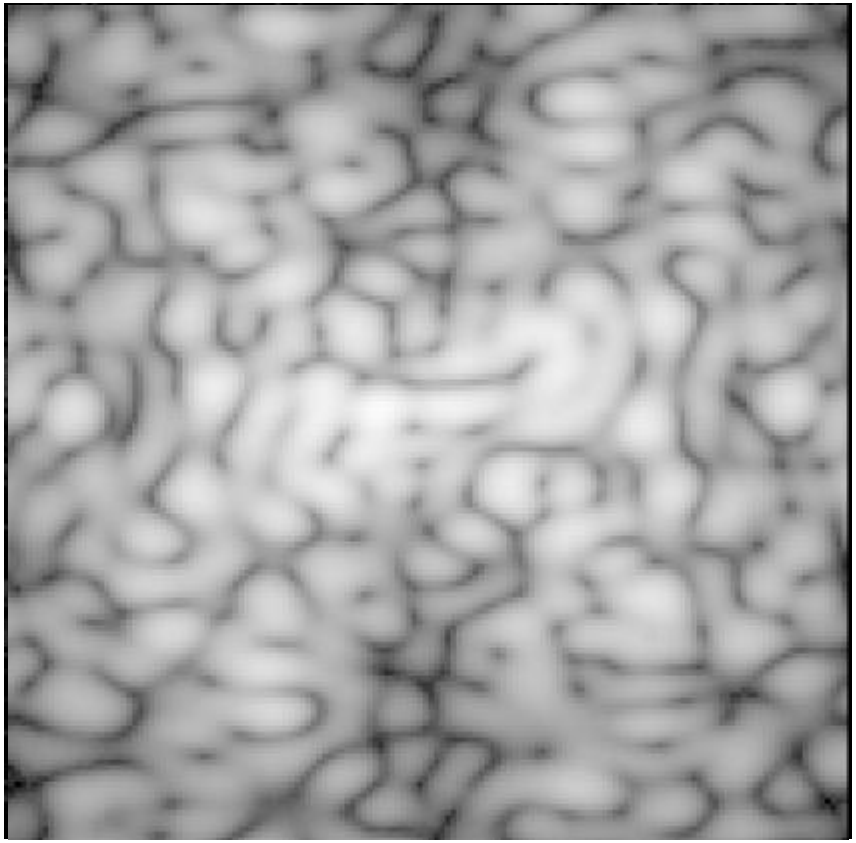
Entrance Pupil



Slide courtesy of A. Give'on

The Scatter Problem

What's left over
After removing diffraction



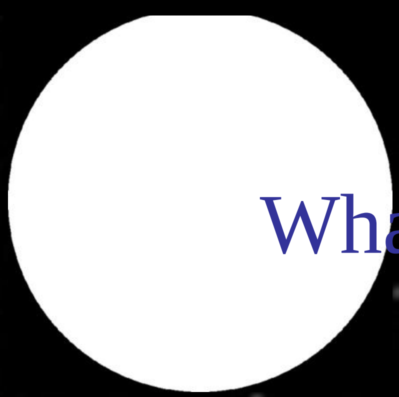
Stellar Coronagraph: Remove Diffraction

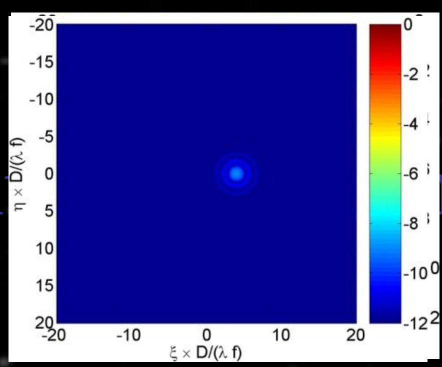
Entrance pupil

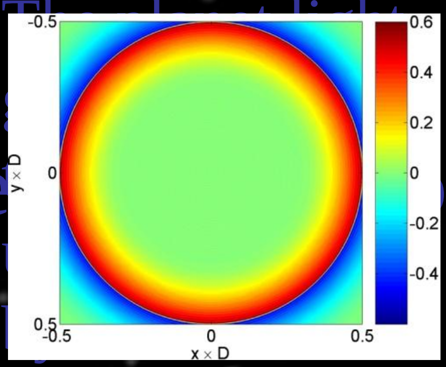
Occulter

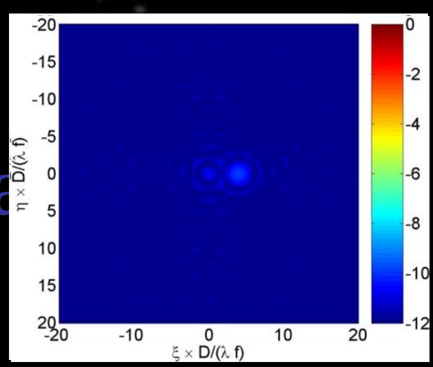
Lyot stop

Image plane





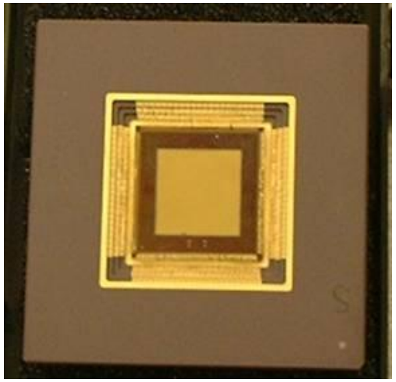




Slide courtesy of A. Give'on

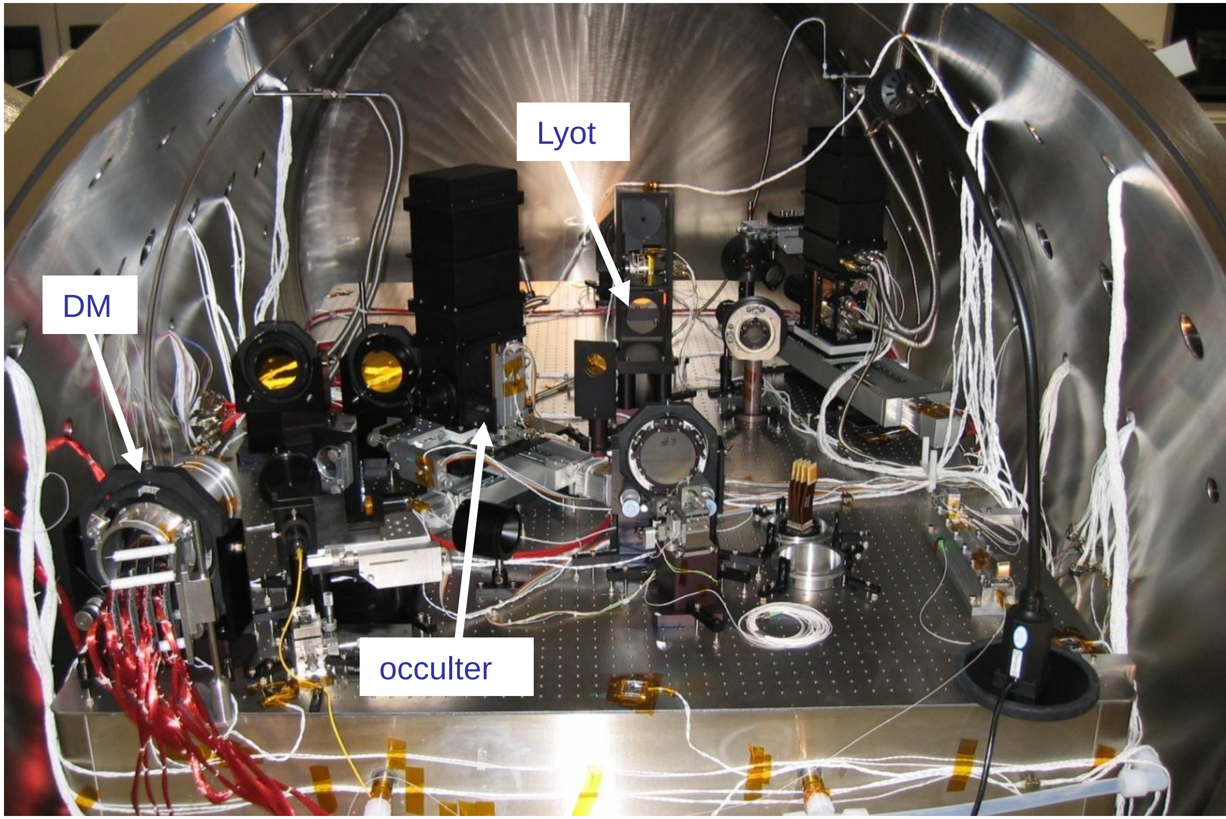
Wavefront Control for Scatter

Xinetics, 64x64 DM



Boston Micromachine
32 x32 MEMS

High Contrast Imaging Testbed (HCIT) provides experimental validation and guidance to models



Hybrid Lyot Coronagraph Experimental Results

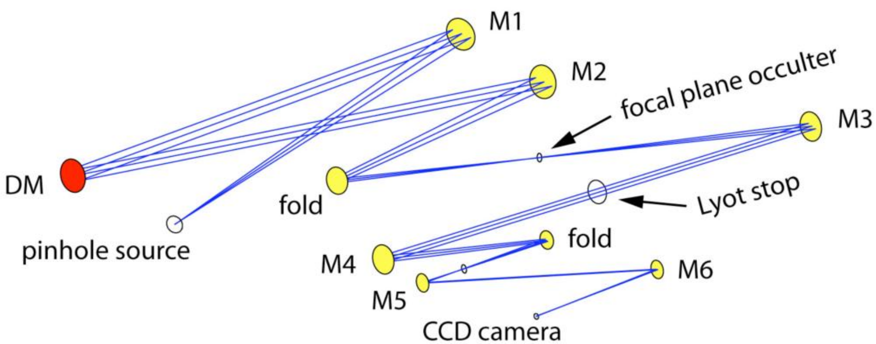
Coronagraph Technology Milestone:
Demonstration of ≤ 10^{-9} contrast w/ hybrid-Lyot Masks @ 3λ/D & 20% BW

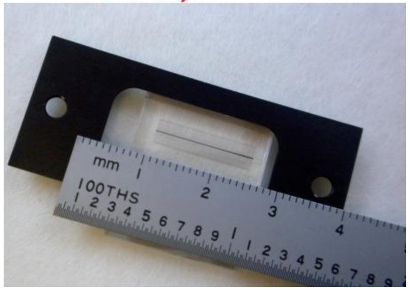
Facility: High Contrast Imaging Testbed 1, JPL

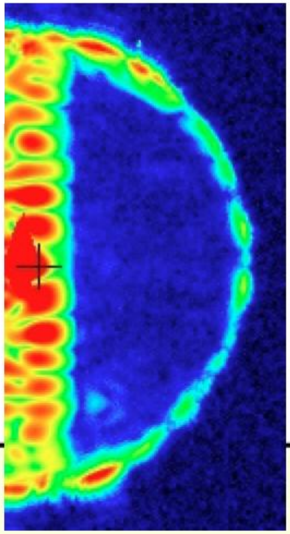
Current Status: 2×10^{-9} contrast @ 3-4 λ/D and 20%

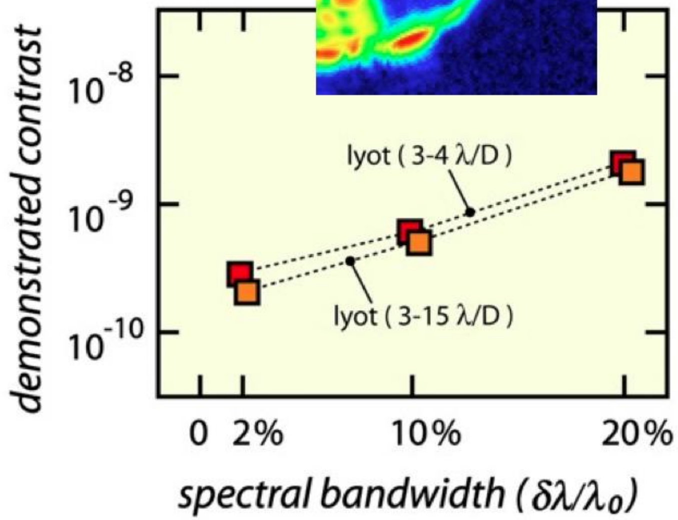
Challenges: Calibration of the dielectric layer during manufacturing.

Future Work: New masks, better contrast at 20% bandwidth. Fabrication and testing of circular masks









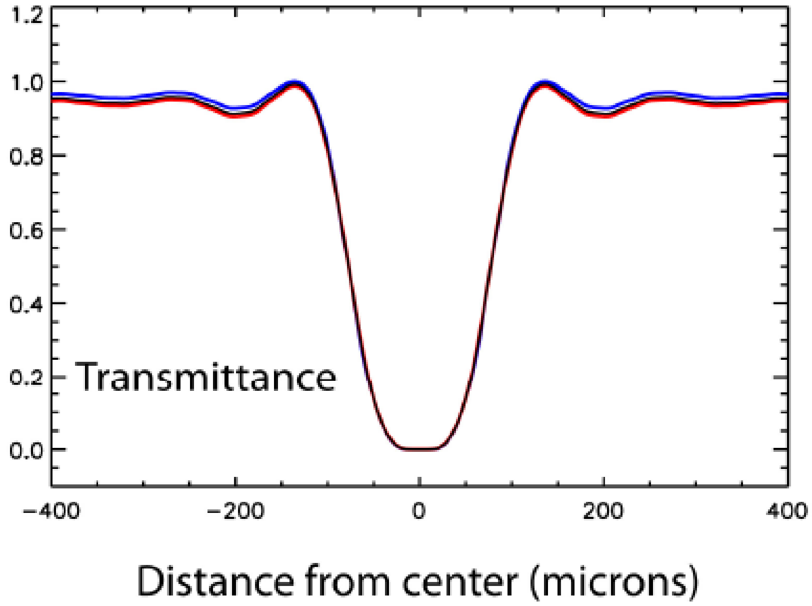
Hybrid Lyot Contrast Achieved to Date (Trauger TDEM)			
	Bandwidth		
Inner Working Angle	2%	10%	20%
3-4 λ/D	$3.2\ 10^{-10}$	$6.0\ 10^{-10}$	$1.9\ 10^{-9}$
3-15 λ/D	$2.0\ 10^{-10}$	$5.2\ 10^{-10}$	$1.9\ 10^{-9}$

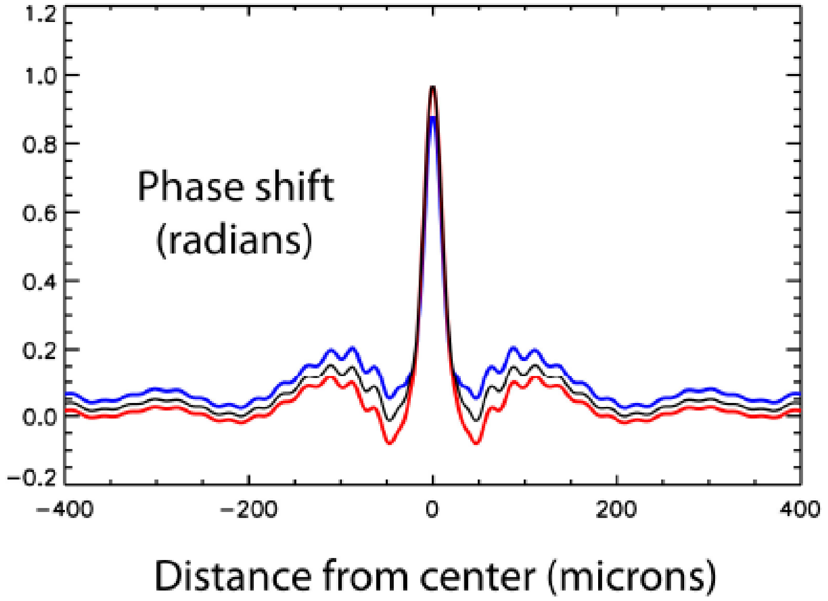
Trauger et al, 2012

Why are we getting stuck?

- Model inaccuracies:
  - Knowledge of as-built mask: OD, phase, dispersion
  - Knowledge of local mask imperfections
- “Large Number Subtraction”
  - Broad-band control balances (relatively) large wavefront control across pupil with chromatic leverage at edge of pupil

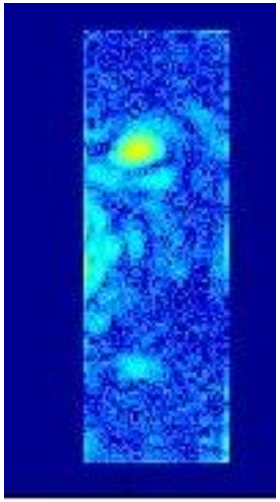
Mask Design vs. As-Built

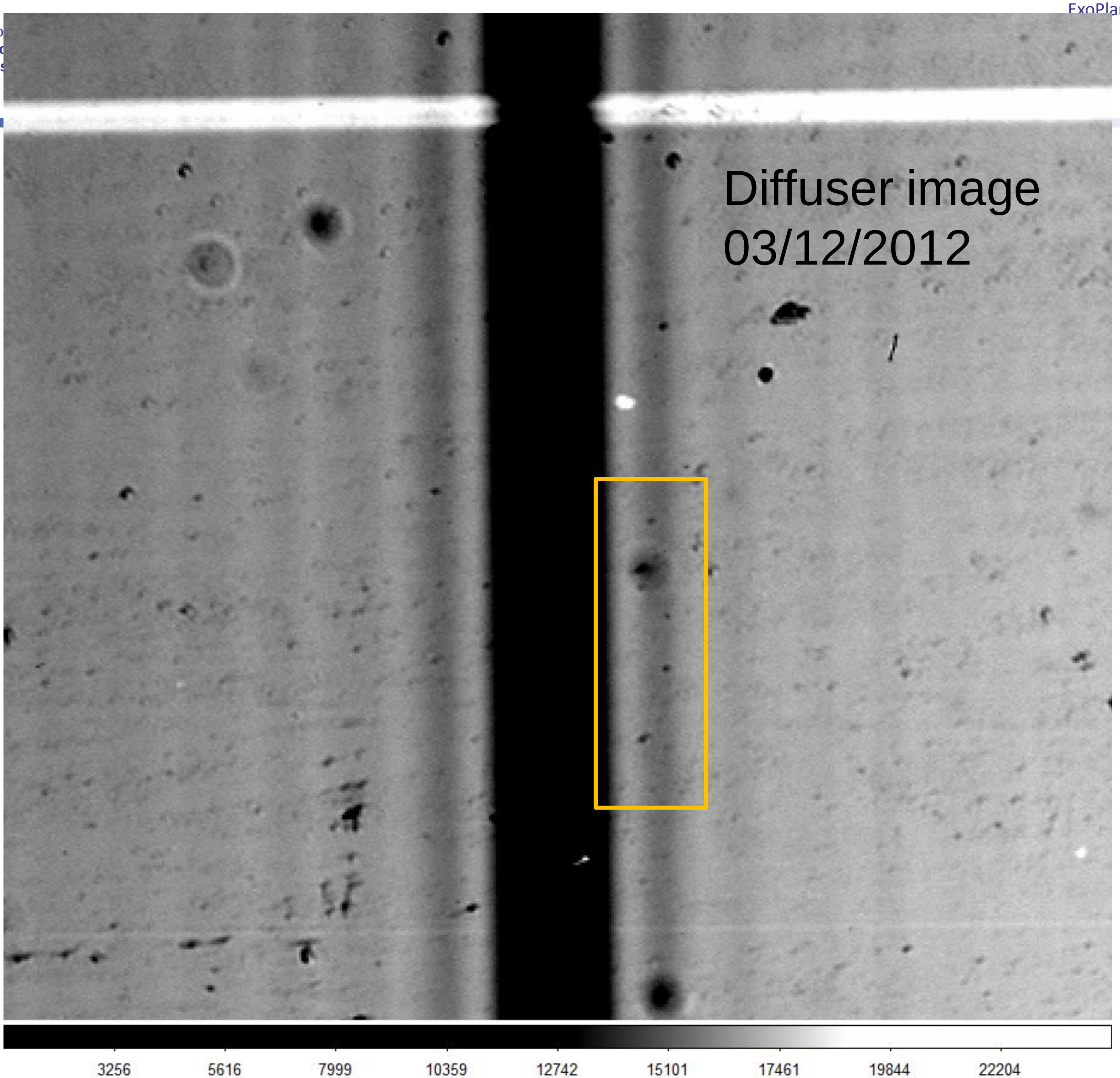




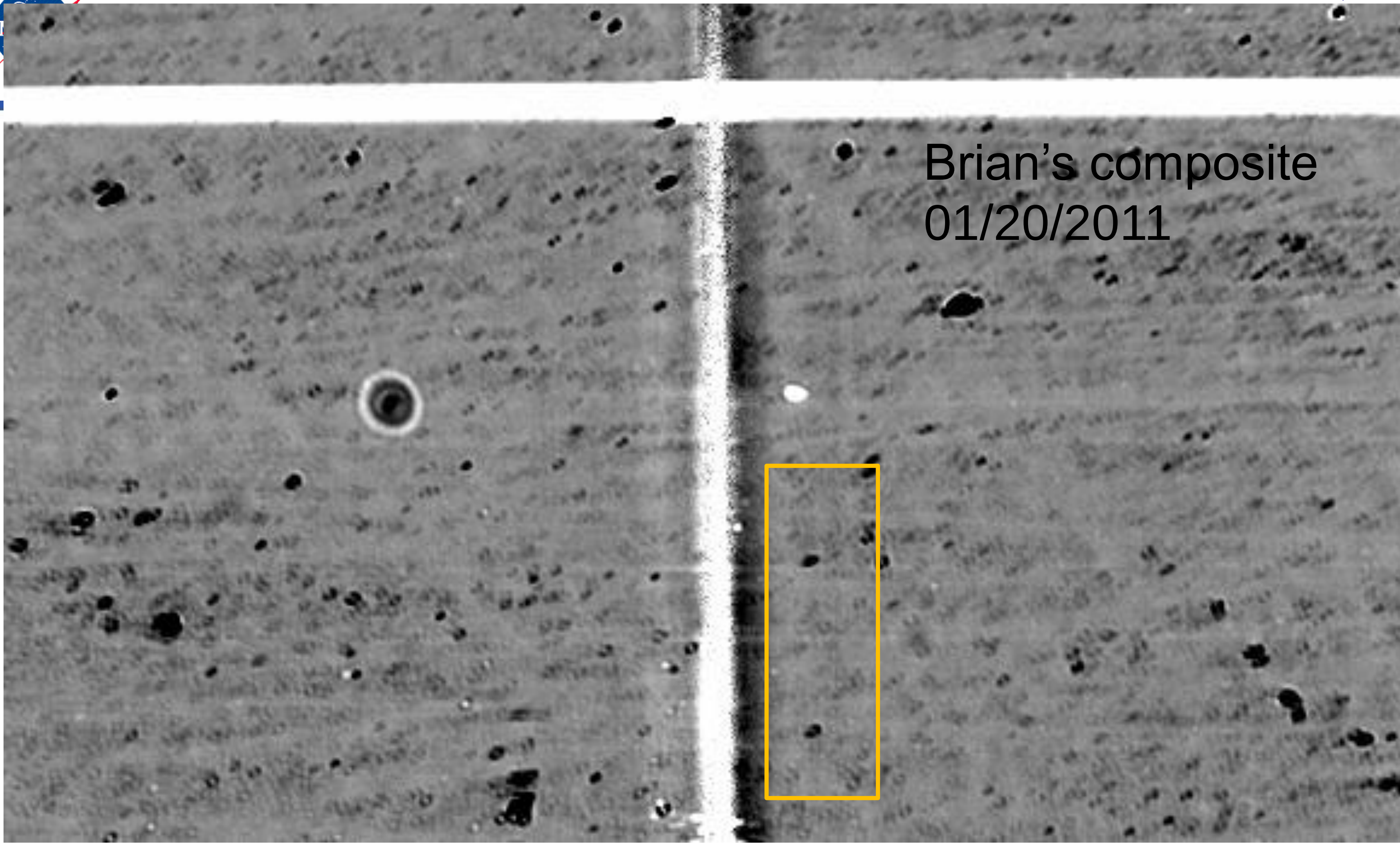
- Mask fabricated by scanning a slit during vacuum deposition.
  - Thickness calibration with crystal monitor
  - Thin film vs. bulk properties.
  - Convolution with effective slit function
  - Dispersion

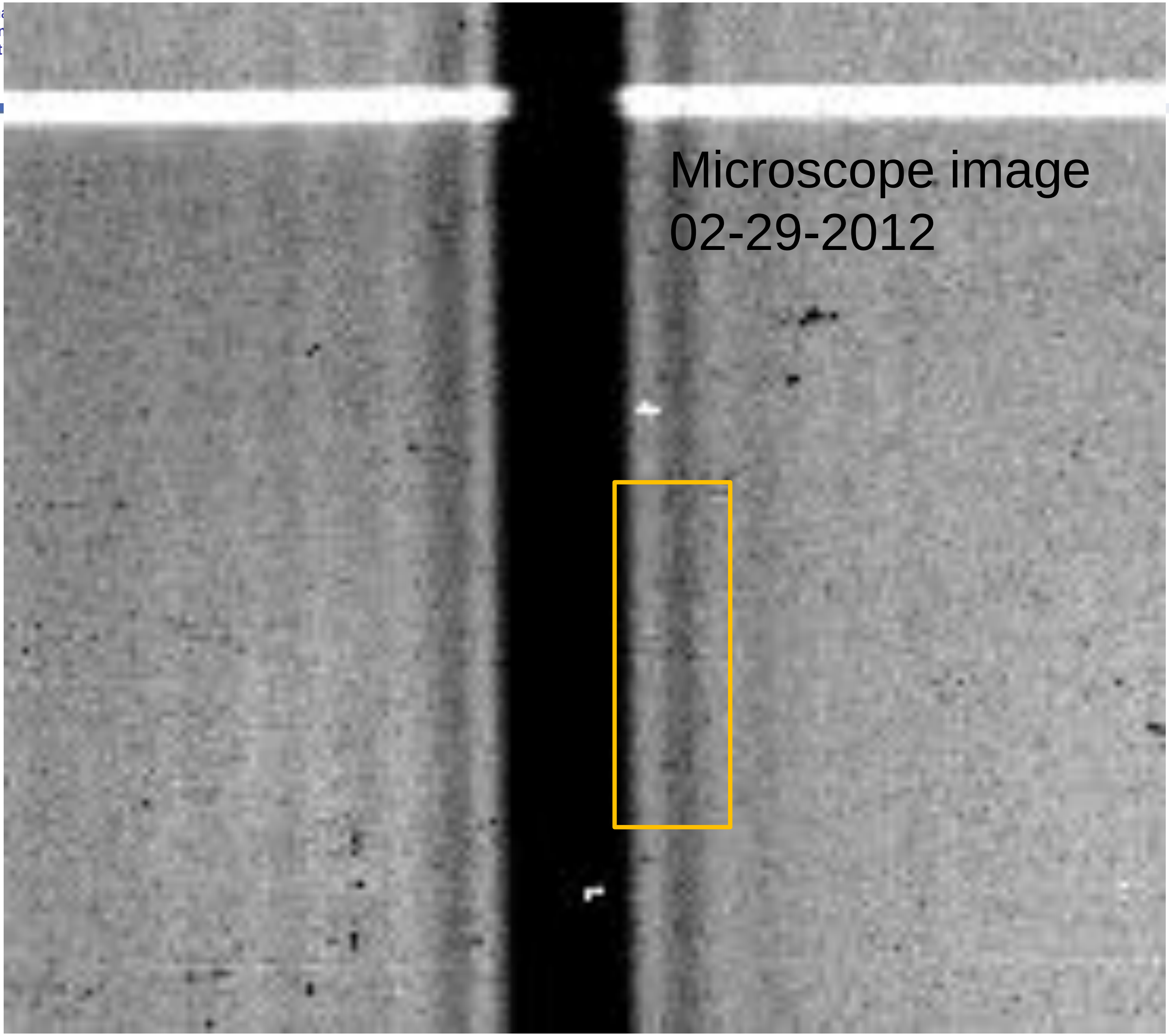
Dark Hole, spring 2012

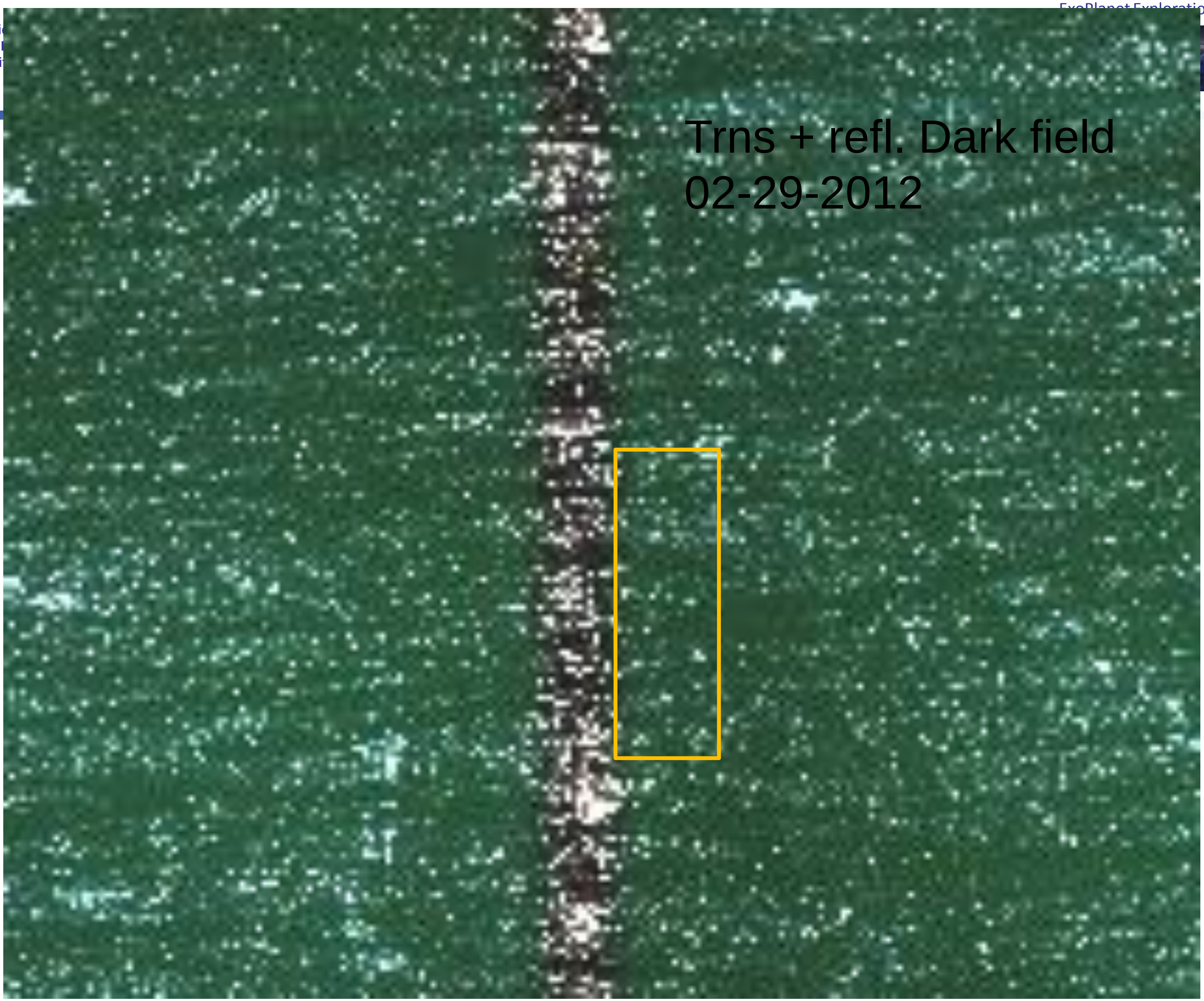




Levine/Osornia


Brian's composite
01/20/2011


Microscope image
02-29-2012



Levine/Osornia

S2.01 Proximity Glare Suppression

(was S2.02 prior to 2012)

- **Lead Center: JPL**
  Participating Center(s): ARC, GSFC

  Starlight Suppression Technologies

- **Advanced apodization mask or occulting spot fabrication technology** controlling smooth density gradients to 10^{-4} with spatial resolutions ~1 µm, low dispersion, and low dependence of phase on optical density, in linear and circular patterns;
- **Metrology for detailed evaluation of compact, deep density apodizing masks**, Lyot stops, and other types of graded and binary mask elements. Development of a system to measure spatial optical density, phase inhomogeneity, scattering, spectral dispersion, thermal variations, and to otherwise estimate the accuracy of masks and stops is needed;
- **Techniques to characterize highly aspheric optic**s;
- **Methods of polarization control and polarization apodization**
- **Components and methods to insure coating uniformity**

S2.01 Continued

- ***Wavefront Control Technologie*s**
- **Development of small stroke, high precision, deformable mirrors and associated driving electronics** scalable to 10^4 or more actuators
  - Process improvements are needed to improve repeatability, yield, and performance precision of current devices;
  - Reliability and qualification of actuators and structures in deformable mirrors to eliminate or mitigate single actuator failures;
  - Multiplexer development for electrical connection to deformable mirrors that has ultra-low power dissipation; and
- **Instruments to perform broad-band sensing of wavefronts and distinguish amplitude and phase in the wavefront;**
  - High precision wavefront error sensing and control techniques to improve and advance coronagraphic imaging performance.
  - **Development of techniques to improve the wavefront stability of the telescope beam**, and/or to mitigate the residual instability. These include but are not limited to: the development of low order wavefront sensors, improved pointing techniques, as well as model-based software algorithms that predict and subtract the instabilities in post-processing.

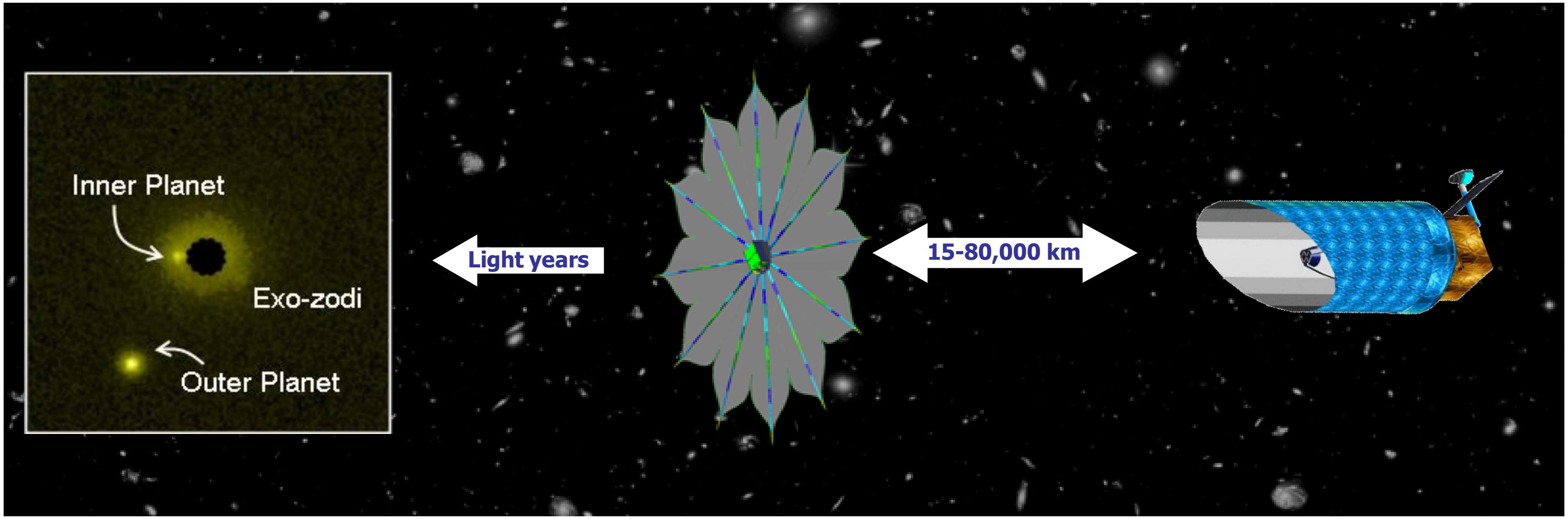
S2.01 cont’d

- ***Optical Coating and Measurement Technologies***
- **Instruments capable of measuring polarization cross-talk and birefringence to parts per million;**
- **Highly reflecting broadband coatings for large (> 1 m diameter) optics**
- **Polarization-insensitive coatings for large optics**

- ***Other Technologies***
- **Artificial star and planet**, point sources, with 1e10 dynamic range and uniform illumination of an f/25 optical system, working in the visible and near infrared.
- **Deformable, calibrated, collimating source** to simulate the telescope front end of a coronagraphic system undergoing thermal deformations.

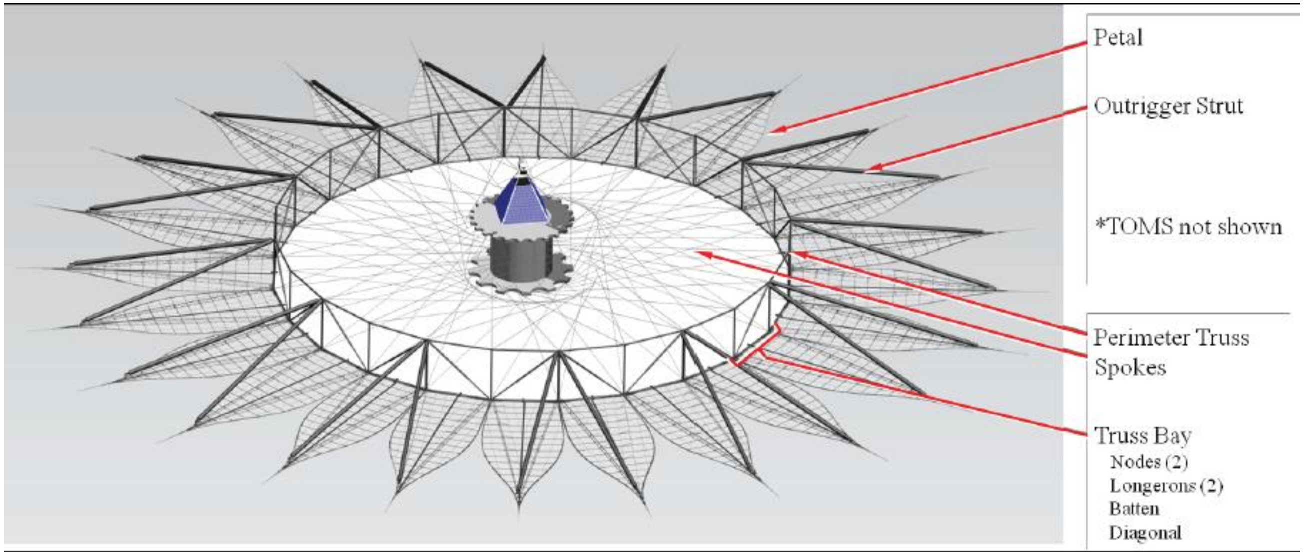
External Occulter

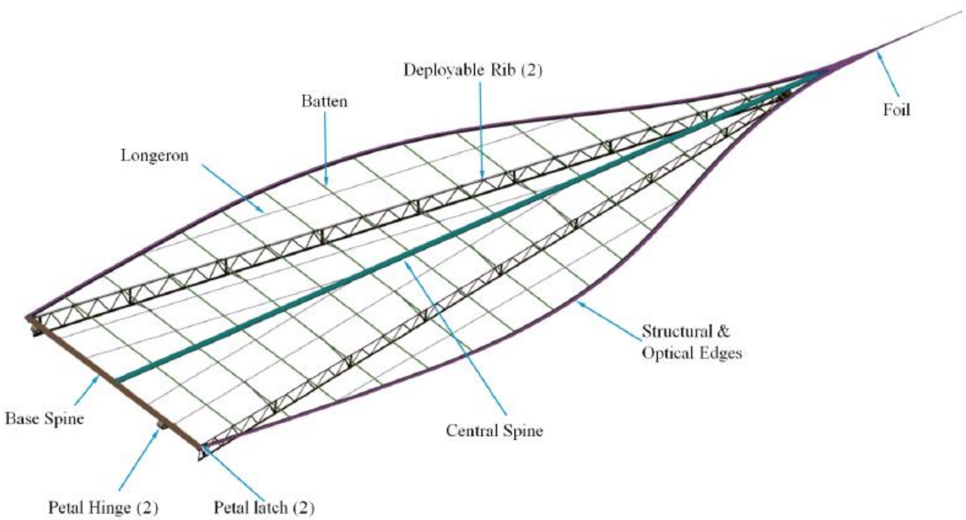
slide courtesy of Chuck Lilly et al., 2007

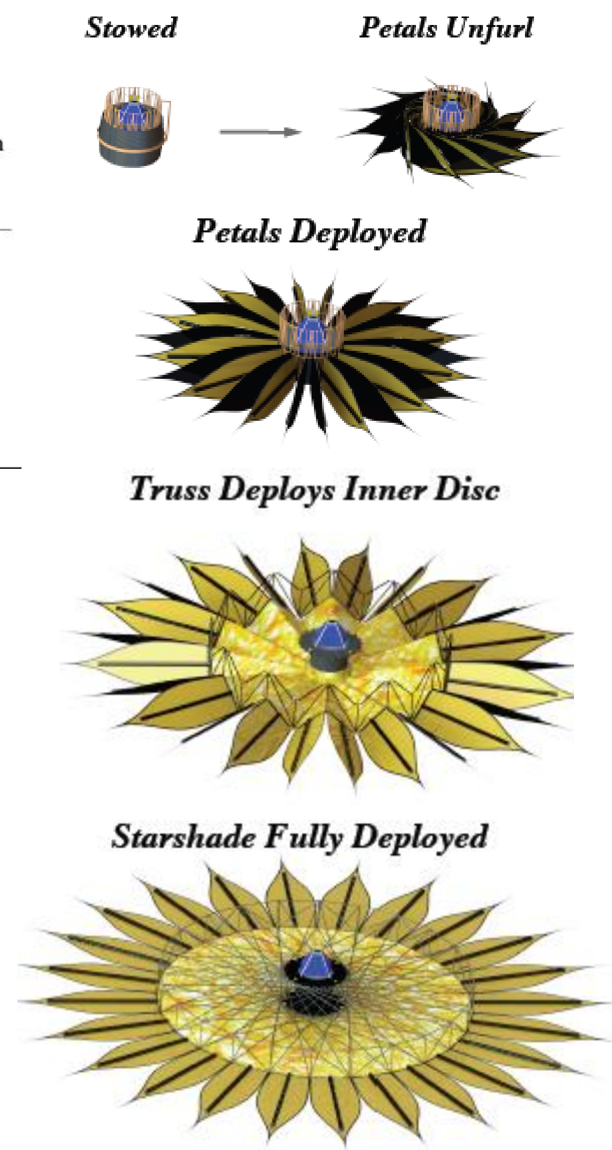


- **Diffraction of a star's light by an "apodized" occulter yields a very dark shadow**
- **A telescope located in the shadow can "peek" around the occulter and directly detect the planet's light**

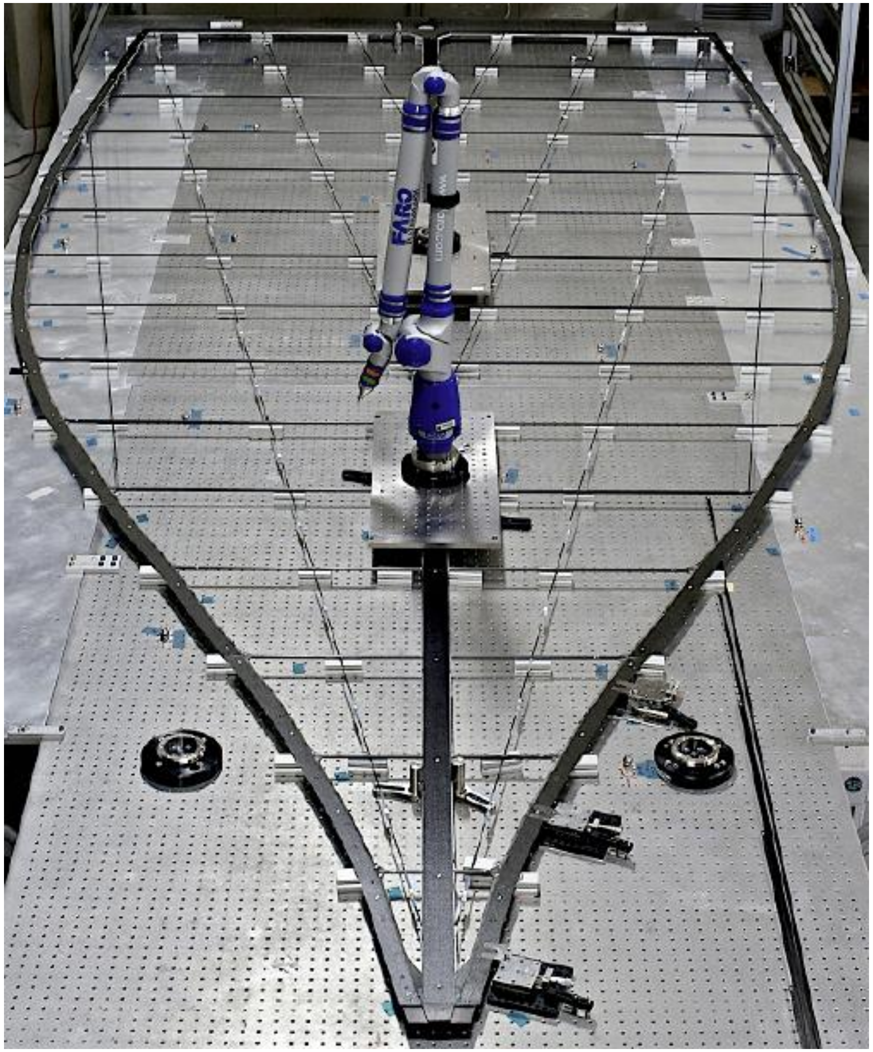
Starshade Construction and Deployment

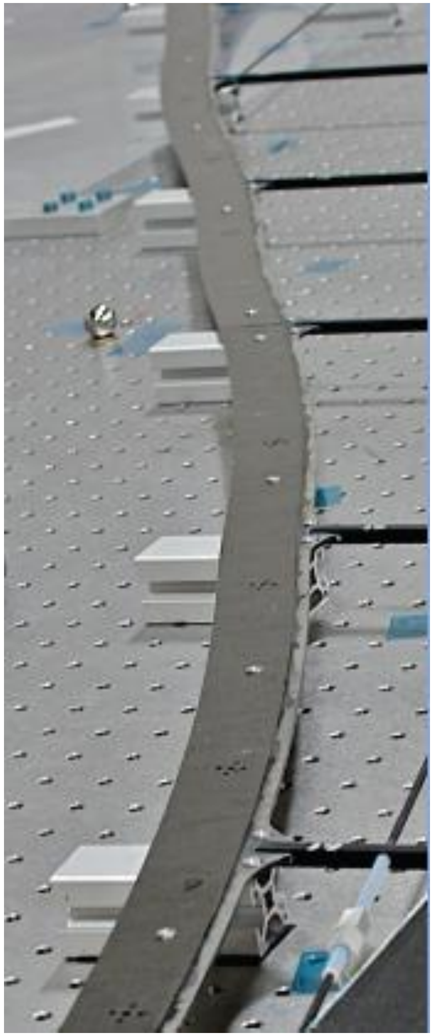






Precision Starshade





S2.02 Precision Deployable Optical Structures and Metrology

was S.03 prior to 2012

- **Lead Center: JPL**
  Participating Center(s): GSFC, Langley RC
- **Sunshades, telescope structures, and starshades**
- Precision deployable structures and metrology for optical telescopes (e.g., innovative active or passive deployable primary or secondary support structures).
- Architectures, packaging and deployment designs for large sunshields and external occulters.
- Mechanical, inflatable, or other precision deployable technologies.
- Thermally-stable materials (CTE < 1ppm) for deployable structures.
- Innovative systems, which minimize complexity, mass, power and cost.
- Innovative testing and verification methodologies.
- The goal for this effort is to mature technologies that can be used to fabricate 16 m class or greater, lightweight, ambient or cryogenic flight-qualified observatory systems.

Current SBIR Awards

- 2011 Phase I:
  - S2.02 Nanolab, Inc.: Nanostructured Super-Black Optical Materials
  - S2.02 Boston Micromachines Corp.: Topographic improvements in MEMs DMs for high-contrast, high-resolution imaging
  - S2.03 Vanguard Space Technologies, Inc.: Fabrication and Measurement of Precision Structures for External Occulter Optical Edges
- 2010 Phase II
  - S2.02 BEAM Engineering for Advanced Measurements: Achromatic Vector Vortex Waveplates for Coronagraphy
  - S2.02 Boston Micromachines Corp: Enhanced Reliability MEMS Deformable Mirrors for Space Imaging Applications
  - S2.02 IRIS AO, Inc. Picometer-Resolution MEMS Segmented DM
- 2009 Phase II
  - S2.02 Boston Micromachines Corp.: Compact Low-Power Driver for Deformable Mirror Systems
  - S2.02 Boston Micromachines Corp.: Enhanced Fabrication Process Development for High Actuator Count Deformable Mirrors

NASA SBIR/STTR Technologies

SBIR
STTR

S2.03-9736 - Fabrication and Measurement of Precision Structures for External Occulter Optical Edges

PI: Mark Schlocker
Vanguard Space Technologies, Inc. - San Diego, CA

Identification and Significance of Innovation

This project proposes to develop an external occulter optical edge and optical edge measurement verification system suitable for astrophysics missions including JWST and the Occulting Ozone Observatory (O3). Key technical challenges lie in manufacturing an optical edge with a cross-section appropriate for an occulter as well as in measuring that edge to the degree of precision required. The focus of this research will be to produce an optical edge with the required cross-section and to measure that edge accurately. Advanced machining techniques will be investigated which may include milling, electrical discharge machining, grinding, and laser machining. Measurement techniques will include scanning laser displacement transducer and computerized measurement machine.

Fabrication and Measurement of Precision Structures for External Occulter Optical Edges

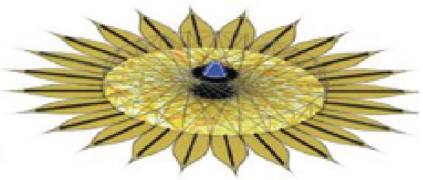


Photo courtesy of JPL

Estimated TRL at beginning and end of contract: (Begin: 1 End: 2)

Technical Objectives and Work Plan

The overall Phase 1 objective is to develop an optical edge with the appropriate cross-section for external occulters for missions such as JWST and the Occulting Ozone Observatory (O3). Important aspects of the research will include material selection, optical edge manufacturing method, and optical edge verification by measurement. The main technical objectives are as follows.

1. Downselect materials for study based on CTE, CME, and manufac turability. Up to four materials will be used to produce test hardware.
2. Choose manufacturing method most appropriate to create an appropriate optical edge with the desired cross-section taper and 25-50 micron radius.
3. Fabricate rectangular test specimens from the chosen materials with the correct optical edge cross-section.
4. Measure optical edge cross-section of test specimens. It may be required to evaluate multiple measurement techniques.

NASA Applications

Near term astrophysics missions requiring occulter optical edges including JWST and the Occulting Ozone Observatory (O3) are the primary focus of research. Any structure requiring extremely tight tolerances on thin panels will benefit. Telescope housings requiring accurate optical baffles are an example.

Non-NASA Applications

Any structure requiring extremely tight tolerances on thin panels will benefit. Telescope housings requiring accurate optical baffles are an example.

Firm Contacts

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FAX: (858) 444-1812

NON-PROPRIETARY DATA

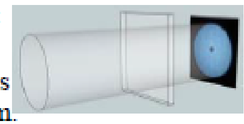
NASA SBIR/STTR Technologies

SBIR
STTR

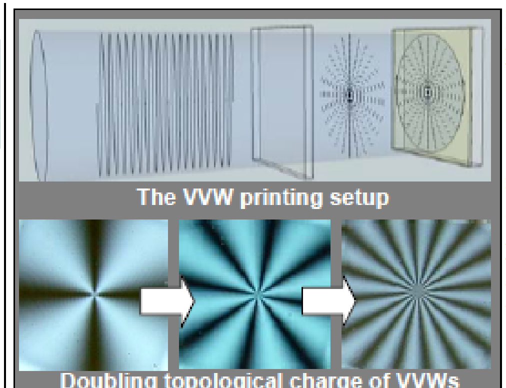
Proposal No. S2.02-8374 - Achromatic vector vortex waveplates for coronagraphy

PI: Dr. Nelson Tabiryan
BEAM Engineering for Advanced Measurements Co., Winter Park, Florida

Identification and Significance of Innovation



Vector vortex waveplates (VVWs) are transparent phase plates capable of blocking starlight while transmitting planetary light at small angular offsets by introducing phase screw dislocation in the beam. Vector vortex coronagraphs would make possible using small aperture telescope systems for detecting exoplanets at nearly diffraction limit of their separation from the star, and detecting planets even closer to the stars with larger aperture telescopes. Recent achievements in diffractive waveplate technology and materials may allow developing VVWs of high topological charge and small singularity area achromatic in a wide spectral range, including visible and infrared.



The VVW printing setup

Doubling topological charge of VVWs

Linear-to-radial polarization conversion allows to print VVWs and double their topological charge without mechanical rotations of the substrate carrying the photoalignment material. Along with better materials, this will allow fabrication of VVWs with enhanced features.

Technical Objectives and Work Plan

Phase 1 Objectives: (a) Proving the feasibility of fabricating VVWs with singularity size smaller than 10 μm, in a large clear aperture ~ 1", and topological charge up to 4; and (b) proving the feasibility of fabricating VVWs with achromatic performance for 700-900 nm wavelengths.

Expected TRL Range at the end of Phase 1(1-9): 3

Phase 2 Objectives: Further reducing the size of singularity to ~2 μm; increasing topological charge to 8; developing VVWs achromatic in different spectral ranges; mitigating ghost images; extending temperature range of VVW operation. Improving and optimizing both photoalignment materials and liquid crystal polymers to create a material base that would allow developing VVWs with quality and specifications meeting various application needs.

Expected TRL Range at the end of Phase 2 (1-9): 5

NASA and Non-NASA Applications

The new generation coronagraphy systems are of interest for many, small and large, astronomical instruments and observatories, including Palomar observatory, the Keck telescope, and the Very Large Telescope in Chile (ESO). The Government projects that would benefit using these components include ACCESS (Actively Corrected Coronagraph for Exoplanet Space Studies, JPL) and NASA's TPF-C (Terrestrial Planet Finder-Coronagraph).

VVWs present also interest for optical micromanipulation (optical tweezers), image processing, microscopy, electro-optical and all-optical switching. and information displays.

Firm Contacts

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Tel. 407-629-1282, Fax 407-629-0460,

BOSTON MICROMACHINES CORPORATION

NASA SBIR/STTR Technologies

Enhanced Reliability MEMS Deformable Mirrors for Space Imaging Applications

SBIR STTR

Boston Micromachines Corporation

PI: Steven Cornelissen

Proposal No.: S2.02-8461

Identification and Significance of Innovation

This project will develop and demonstrate a reliable, fault-tolerant microelectromechanical deformable mirror (MEMS-DM) technology, filling a critical gap in NASA's roadmap for future coronagraphic observatories. The project outcomes include innovative advances in component design and fabrication and substantial progress in development of high-resolution deformable mirrors suitable for space-based operation.

Estimated TRL (1 – 9) at beginning and end of contract: [2 -> 3]

Boston Micromachines MEMS deformable mirrors for adaptive optics applications

Technical Objectives and Work Plan

Task	M1	M2	M3	M4	M5	M6
1. Generate modified actuator design and lithographic mask set						
2. Fabrication of actuator arrays						
3. Design and fabrication of current-limiting resistor boards						
4. DM actuator reliability testing using only current-limiting resistor board.						
5. Packaging and Electromechanical test of high-reliability actuator arrays						
6. High-reliability DM actuator reliability testing						

NASA and Non-NASA Applications

The development of reliable deformable mirrors with a low amount of single actuator failures has applications relative to NASA needs for space astronomy systems (such as TPF-C, TPF-I, EPIC, etc.)as well as other Government agencies and commercial markets. The universal benefit to all applications is a reliable MEMS device that can withstand the voltage spikes and environmental changes that currently cause failure in MEMS DMs, leading to more effective correction capabilities and longer device use in the field. Specific markets where this could be applied are biological imaging, laser communication and aerial surveillance.

Firm Contacts

PI Steven Cornelissen *sac@bostonmicromachines.com*
SBC Official: Paul Bierden *pab@bostonmicromachines.com*
617.868.4178 TEL 616.868.7996 FAX

NON-PROPRIETARY DATA

NASA SBIR/STTR Technologies

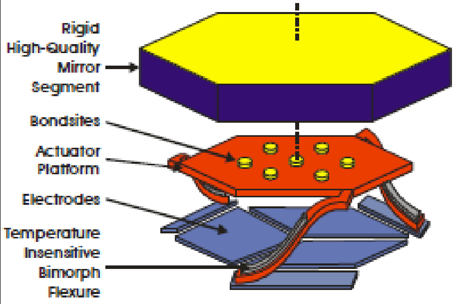
S2.02-9446 - Picometer-Resolution MEMS Segmented DM

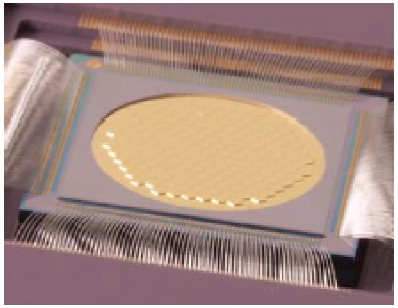
PI: Dr. Michael Helmbrecht
Iris AO, Inc., Berkeley, CA

Identification and Significance of Innovation

- DMs used for coronagraphy must be capable of picometer resolution
- MEMS DMs have relatively large surface figure errors in unpowered state
- Fabrication processes must be matured to improve unpowered surface figure
- DM design can be modified to compensate for remaining residual errors while maintaining picometer resolution

Expected TRL Range at the end of Contract (1-9): 3





Technical Objectives and Work Plan

Technical Objectives
- Mitigate chip bow effects that cause deformation in the array
- Eliminate systematic tilts in the mirror arrays
- Mitigate random segment position variations
- Continue to improve DM yield by tracking and codifying fabrication-process defects and failure modes
- Design a picometer resolution 939 actuator, 313-segment DM

Work Plan
1) Chip-bow mitigation
2) Systematic-tilt elimination and segment-position-variation reduction
3) 313 segment picometer-resolution DM design

NASA and Non-NASA Applications

NASA Applications
Visible Nulling Coronagraph for ATL:AST, DAViNCI, and EPIC

Non-NASA Applications
Atmospheric correction
Free-space laser communications
Fiber alignment/coupling for fiber spectragraphs
Laser beam shaping
Retinal imaging
Microscopy

Firm Contacts

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(510) 849-2375

NON-PROPRIETARY DATA

NASA SBIR/STTR Technologies

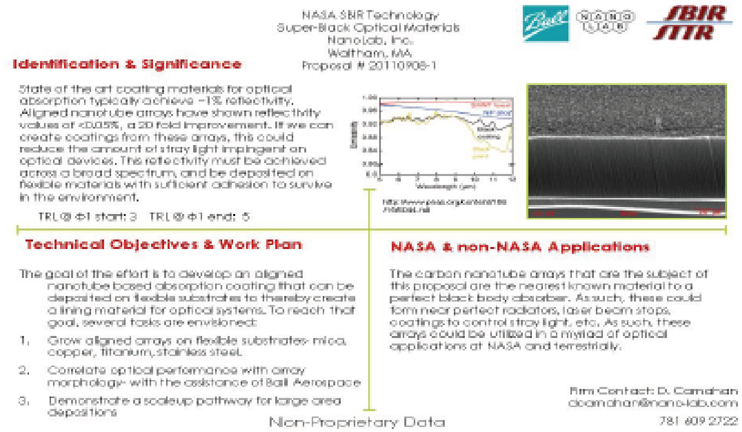
S2.02-8177 - Nanostructured Super-Black Optical Materials

PI: David Carnahan
NANOLAB, INC - Waltham, MA

Identification and Significance of Innovation

NASA faces difficulties in characterizing faint astrophysical objects within the glare of brighter stellar sources. Achieving a very low background requires control of scattered light. Aligned arrays of carbon nanotubes have been recognized as having world-leading optical absorption, far above competing materials. A team at GSFC noted that nanotubes have the "potential to provide order-of-magnitude improvement over current surface treatments and a resulting factor of 10,000 reduction in stray light when applied to an entire optical train." The nuances of the array structure, such as angular alignment, diameter, length, and top-surface roughness control their optical properties, and these need to be characterized if we wish to tailor these for specific applications. Further, the arrays grown to date are often poorly adhered to their substrates. NanoLab will grow CNT on metallic foils, assess their adhesion, and correlate their optical properties with morphology and growth conditions.

Estimated TRL at beginning and end of contract: (Begin: 2 End: 4)


NASA SBIR Technology
Super-Black Optical Materials
Nanolab, Inc.
Waltham, MA
Proposal # 20110908-1

Identification & Significance

State of the art coating materials for optical absorption typically achieve ~1% reflectivity. Aligned nanotube arrays have shown reflectivity values of <0.05%, a 20 fold improvement. If we can create coatings from these arrays, this could reduce the amount of stray light impingent on optical devices. The reflectivity must be achieved across a broad spectrum, and be deposited on flexible materials with sufficient adhesion to survive in the environment.

TRL @ Φ1 start: 3 TRL @ Φ1 end: 5

Technical Objectives & Work Plan

The goal of the effort is to develop an aligned nanotube based absorption coating that can be deposited on flexible substrates to thereby create a lining material for optical systems. To reach that goal, several tasks are envisioned:

1. Grow aligned arrays on flexible substrates- mica, copper, titanium, stainless steel.
2. Correlate optical performance with array morphology- with the assistance of Ball Aerospace
3. Demonstrate a scaleup pathway for large area depositions

NASA & non-NASA Applications

The carbon nanotube arrays that are the subject of this proposal are the nearest known material to a perfect black body absorber. As such, these could form near perfect radiators, laser beam stops, coatings to control stray light, etc. As such, these arrays could be utilized in a myriad of optical applications at NASA and terrestrially.

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781 609 2722

Non-Proprietary Data

Technical Objectives and Work Plan

The optical properties of an aligned array depend upon the nanotube morphology, which in turn depends upon the catalyzation and the growth processes used to create it. During the Phase I effort, NanoLab and Ball Aerospace will work to correlate the optical performance of aligned array absorbers to the morphology of the arrays, and also to the catalyzation and growth conditions. We will produce these coatings on flexible substrates, so the coating can be applied to equipment. Specifically, we will:
1. Develop scalable processes to grow CNT arrays on flexible substrates with good adhesion.
2. Measure the optical characteristics of arrays made with varied growth parameters to determine the influence of nanotube diameter, site density, alignment, length, graphitization, etc. on these characteristics.
3. Establish control over the parameters that are correlated to optical performance, so that tailored absorbers can be designed and manufactured.

NASA Applications

NanoLab and our subcontractor, Ball Aerospace, view this coating as a leap-ahead technology, compared to the Z306 polyurethane black and others that are currently used as absorptive coatings in telescopes and other optical systems. We also recognize that near perfect black body materials have applications as radiators, beam dumps, and calibration tools.

Non-NASA Applications

Calibration of terrestrial pyrometers, spectrometers, etc require black body materials like the nanotube-black can provide. Other applications for aligned arrays include gecko-foot adhesives, electrodes, thermal interface materials, etc.

Firm Contacts

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NON-PROPRIETARY DATA

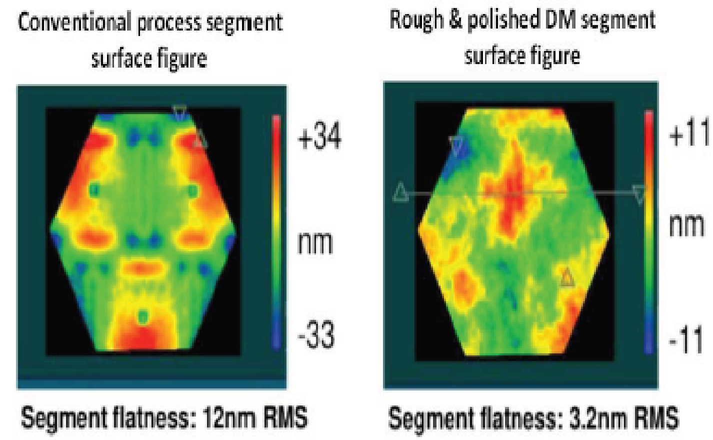
NASA SBIR/STTR Technologies

S2.02-8592 - Topography improvements in MEMS DMs for high-contrast, high-resolution imaging

PI: Steven Cornelissen
Boston Micromachines Corporation - Cambridge, MA

Identification and Significance of Innovation

This project will demonstrate an innovative microfabrication process to substantially improve the surface quality achievable in high-resolution continuous membrane MEMS deformable mirrors (DMs). Specific aims include twofold improvement in small-scale surface flatness and substantial reductions in sub-aperture scale diffractive losses. Such wavefront control devices will fill a critical technology gap in NASA's vision for high-contrast, high-resolution space based imaging and spectroscopy instruments.



Estimated TRL at beginning and end of contract: (Begin: 2 End: 3)

Technical Objectives and Work Plan

In the proposed project, we will develop processes and manufacturing innovations that collectively reduce or eliminate midscale spatial wavelength defects. To reduce print-through, we will explore an innovative chemomechanical polishing technique. To reduce stress-induced scalloping, we will employ a compensating stress reduction layer on top of the mirror after structural release, and before deposition of the reflective coating. And to Eliminate etch access holes we will experiment with HF release techniques, including both liquid and vapor HF processes, to reduce the optical effects of etch access holes by reducing their size and their number.
To achieve the proposed objectives the following 5 tasks will be performed:
Task 1. Generate mask layout for DM test structures
Task 2. Fabricate DM test structures
Task 3. Coat DM test structures and characterize surface figure
Task 4. Characterize DM HF release process space to mitigate etch access hole related diffractive losses.
Task 5. Develop compensating thin film deposition process to mitigate scalloping in DM surface

NASA Applications

There are many applications relative to NASA where there is a need for deformable mirrors with improved surface finish and quality over the current state-of-the-art. NASA needs include any ground or space based telescope or imaging system including TPF-C, TPF-I, EPIC and PECO. With the topography improvements proposed in this project, less light will be lost in the optical path, improving the effectiveness of all applications taking advantage of deformable mirrors.

Non-NASA Applications

There are applications relative to the requirements of government agencies and commercial markets which are in need of deformable mirrors with improved surface finish and quality over the current state-of-the-art. These include optical communication, pulse shaping and biological imaging.

Firm Contacts

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NON-PROPRIETARY DATA

The End

BACKUP SLIDES

Guyon (Univ of Arizona) / Kern (JPL) Phase Induced Amplitude Apodization

Coronagraph Technology Milestone #1:
Demonstration of ≤ 10^{-9} contrast with PIAA coronagraph at 2λ/D in laser light

Current Status: ~~3×10^{-8}~~ 4×10^{-9} contrast @ 2-3 λ/D.

Challenges: Uncontrolled background, image motion.

~ 1 order magnitude improvement

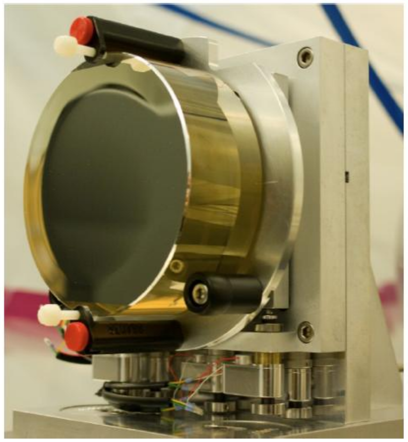
Coronagraph Technology Milestone #2:
Demonstration of ≤ 0.01 λ/D pointing stability w/ Low Order Wavefront Sensor.

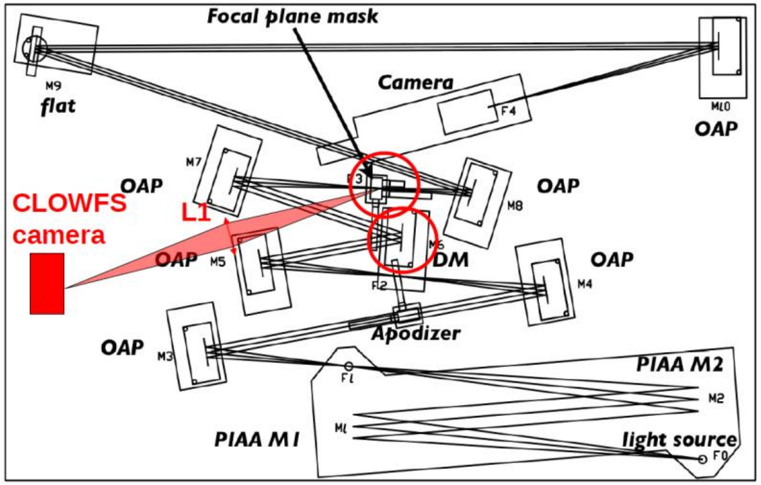
Current Status: Closed-loop tracking at 1.6 Hz, 0.03 f λ/D rms residuals.

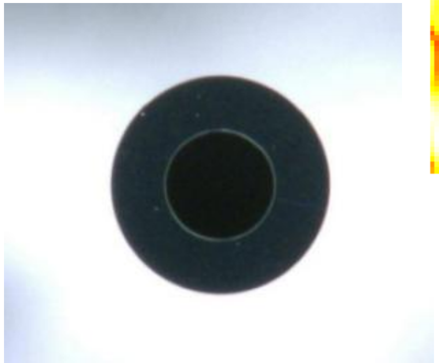
Challenges: Hardware for closed-loop control in vacuum.

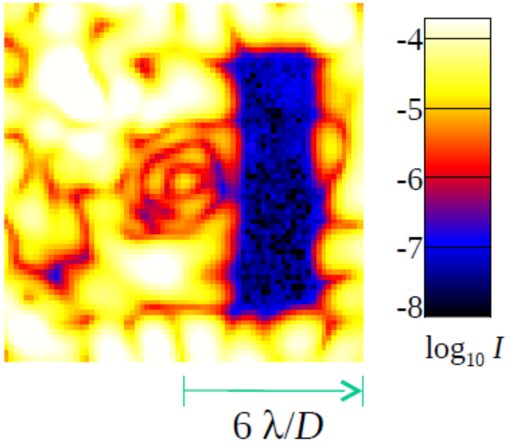
Facility: High Contrast Imaging Testbed -2 , JPL.

Future Work: Milestone #2 runs in 1/2012. Milestone #1 runs afterwards then proceed with TDEM10 for 10^{-9} contrast at 2λ/D in 10% BWD.







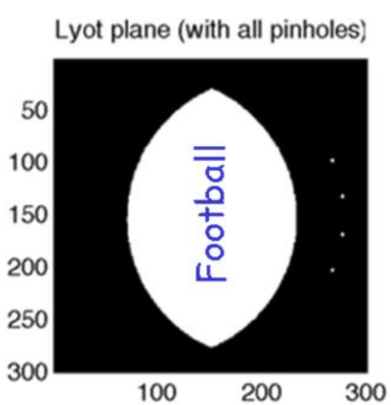


LOWFS uses light blocked by the focal plane mask to measure low order aberrations with high sensitivity

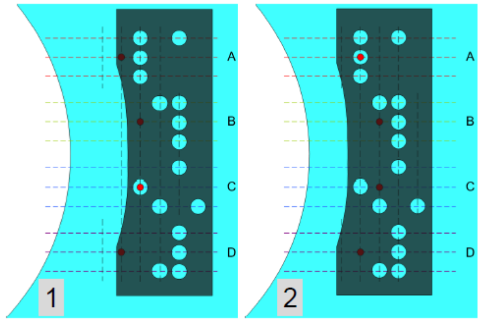
Trauger Guyon Krist Kendrick Clampin Kasdin Figer

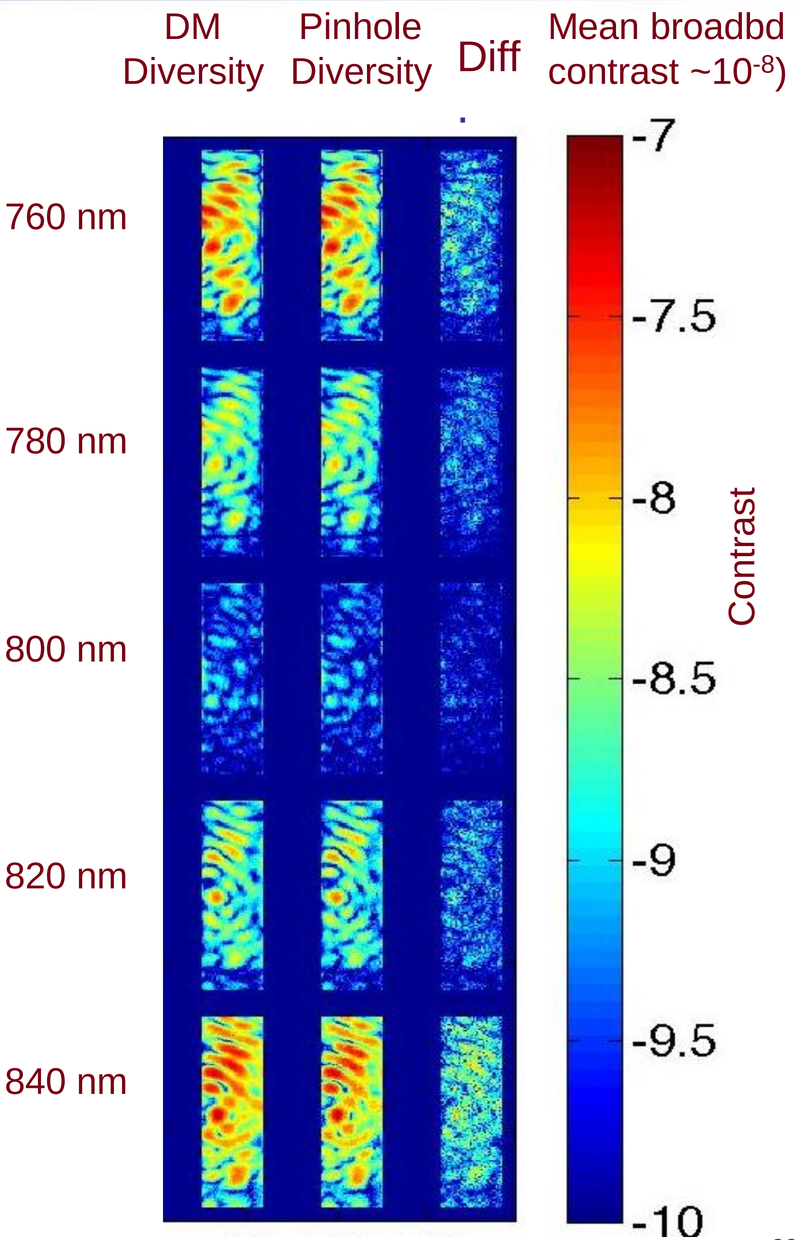
Speckle Sensing TDEM09 (Noecker, Shaklan, Kendrick)

- Use set of pinholes at Lyot stop to provide a reference field.
  - Provides an independent means of electric field estimation.
  - Compare to DM phase diversity.
- Advantage over DM diversity:
  - DM actuator motion not known perfectly
  - Can self calibrate the pinholes using pairs by blocking the Lyot Stop and obtaining a clean reference WF
- Working in broad-band light
  - Agreement between the two techniques to s=18% over the 10% bandpass meets milestone level (goal of s=20%).
- Second step add incoherent background light to show that estimation technique remains unbiased
- All Milestone runs have been completed and a Milestone report is being prepared for ExoTAC review

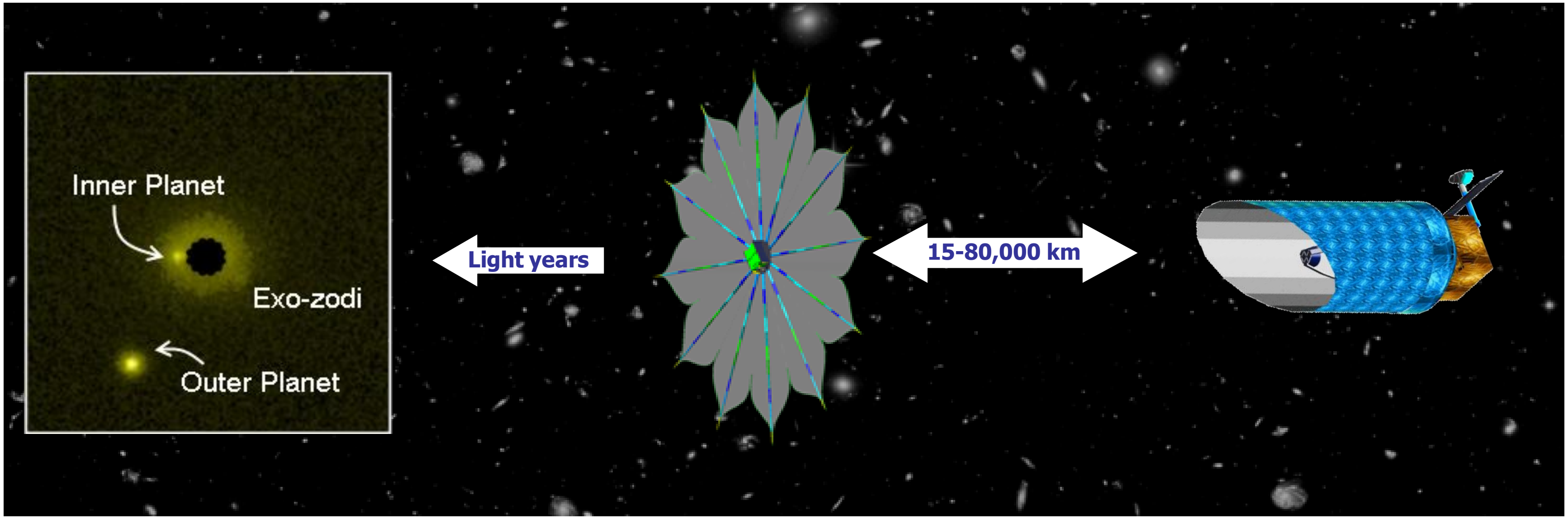


Sliding binary mask





Starshade Overview



- **Diffraction of a star's light by an "apodized" occulter yields a very dark shadow**
- **A telescope located in the shadow can "peek" around the occulter and directly detect the planet's light**

slide courtesy of Chuck Lilly et al., 2007

Starshade Development
N. J. Kasdin (Princeton University)

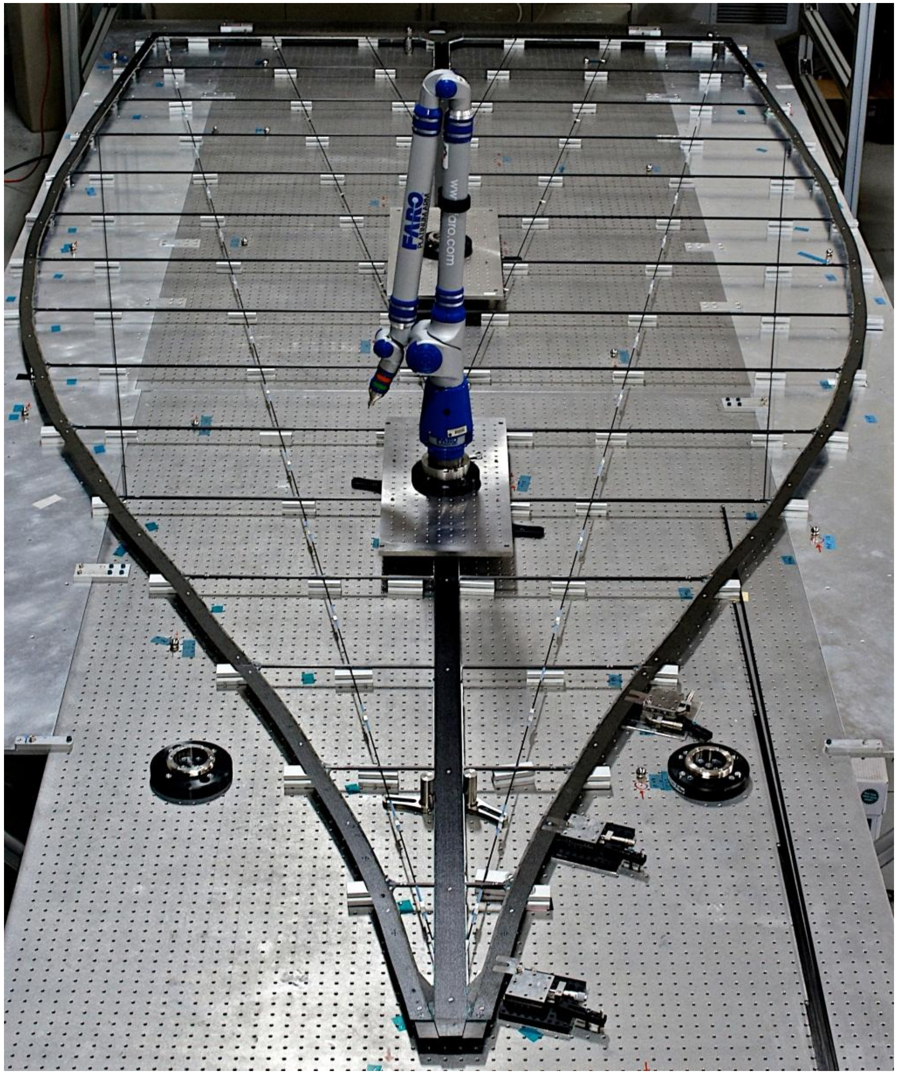
Starshade Technology Milestone: Demonstrate through mechanical measurements on a single petal made of flight-like materials using optical simulations based on those measurements that contrasts of $\leq 3 \times 10^{-10}$ at the inner working angle can be achieved.

Facility: Assembly Handling Facility (Bldg 299), JPL.

Current Status: The measurements have been completed and are within milestone specifications.

Challenges: Mechanical measurements over a large structure.

Future Work: Milestone report to be completed in 2012.



The Challenge

Imagine looking for a bump 1/100 the thickness of a human hair…

…on the slopes of Mt. Everest!!

90 microns / 100 = 9e-7 m

9000 m = 9e3 m

That's a ratio of 1e10, same as Earth to Sun contrast!!

John Krist (JPL/Caltech)
End-to-End Coronagraph Modeling

Coronagraph Technology Milestone #1:

Demonstration of fast & accurate propagator for Hybrid Lyot, PIAA, and Vector Vortex coronagraphs with ≤ 1% errors when compared to more rigorous reference algorithms, ≤ 48 hours to compute 2-DM (48x48) 5-wavelength response matrix on a modern workstation.

Coronagraph Technology Milestone #2:

Using propagators from Milestone #1, determine parameters for each coronagraph to achieve ≤ 10^{-10} mean contrast over λ = 500–600 nm in a realistically aberrated system with wavefront control.

Challenges: Design of Hybrid Lyot Masks has taken longer than anticipated.

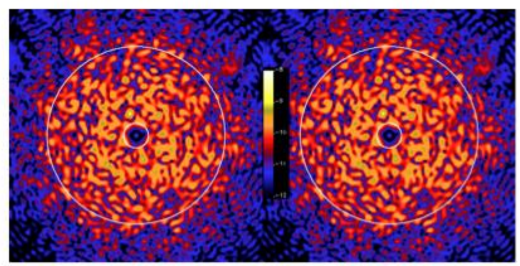
Current Status:

1st Milestone: PIAA and Vector Vortex completed. Hybrid Lyot still in work.

2nd Milestone: PIAA completed, Vector Vortex in progress.

Image Plane Fields

Reference method Fast method



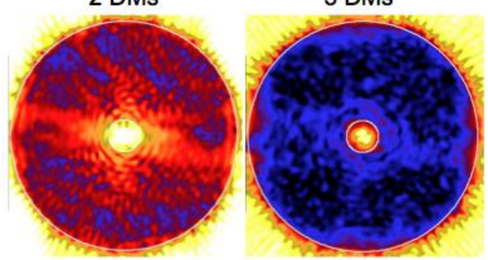
Derived a suitable binary post-apodizer and a means to represent it with limited wavefront sampling.

Developed and optimized propagation codes for both accuracy and speed.

Verified results against reference methods.

Default errors 2 DMs

20x reduced errors 3 DMs



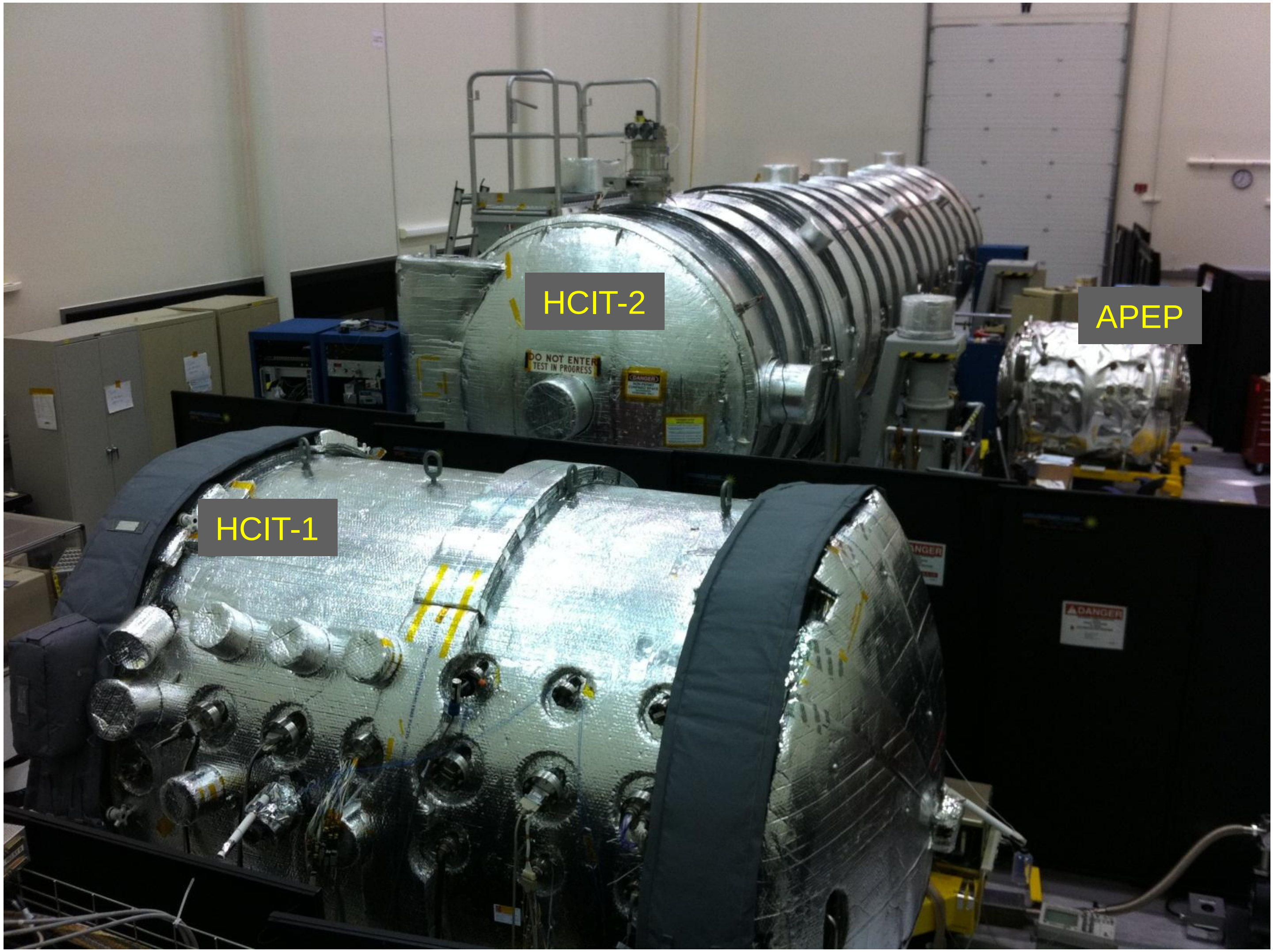
Used propagators and wavefront control methods (EFC) to create dark holes around sources.

Determined current PIAA optics need to be 20x better to reach 10^{-10} broadband contrast.

Identified need for 3rd DM after PIAA optics to control optical errors between PIAA and occulter.

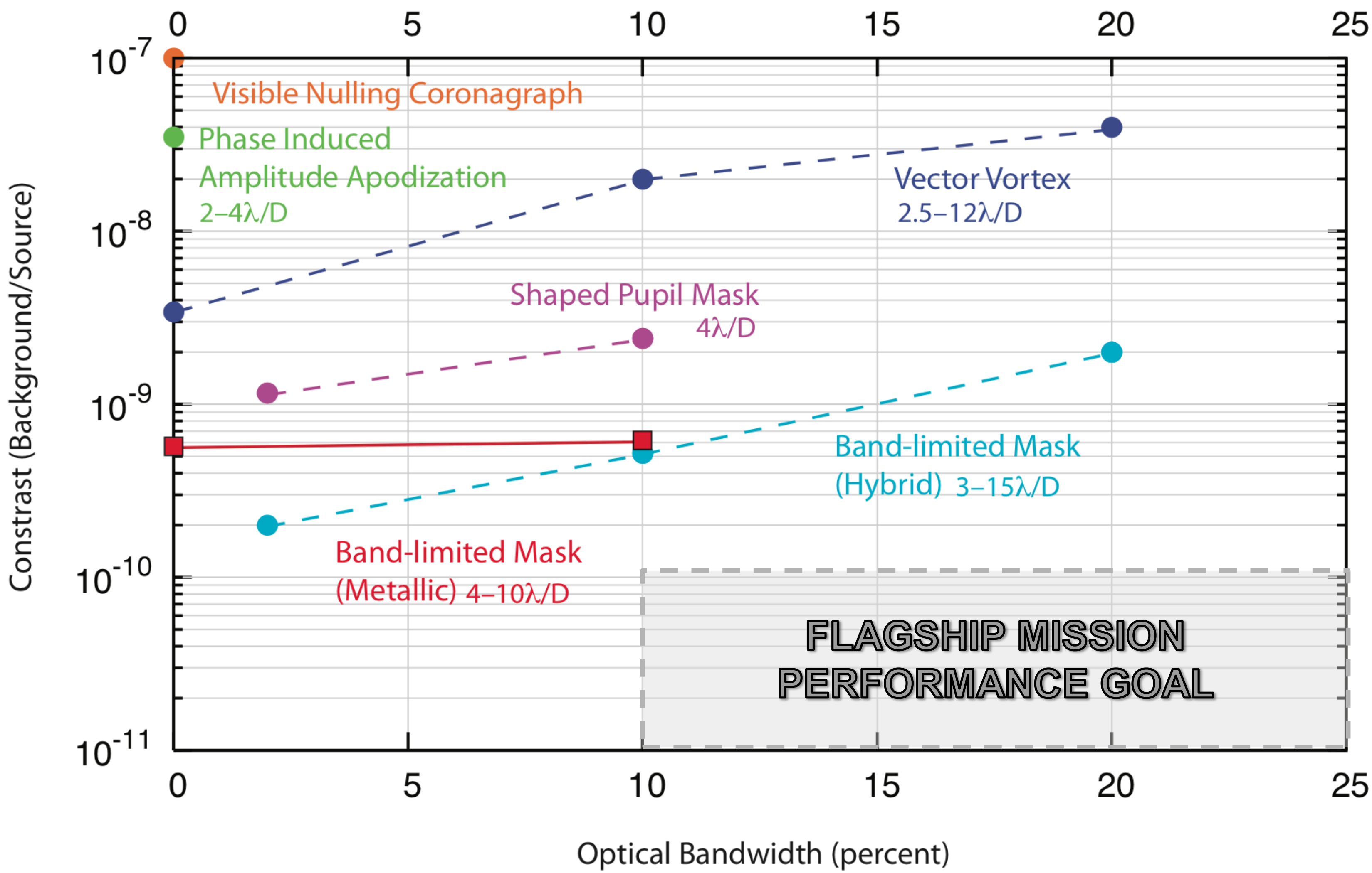
Trauger Guyon Krist Kendrick Clampin Kasdin Figer

Infrastructure Upgrades in FY'11



SIM chamber retrofit (HCIT-2) and new visible nuller chamber (APEP) provide augmented test capacity for starlight suppression demonstrations in JPL Building 318 high bay.

Coronagraph Contrast Performance Achieved to Date



Noecker/Kendrick (Ball Aerospace) & Shaklan (JPL) Advanced Speckle Sensing

Coronagraph Technology Milestone:

Demonstration of ≤ 20% rms difference between contrast maps obtained using pinhole vs standard DM phase diversity approach, with ≤10^{-8} contrast using Lyot Masks @ 10% BWD.

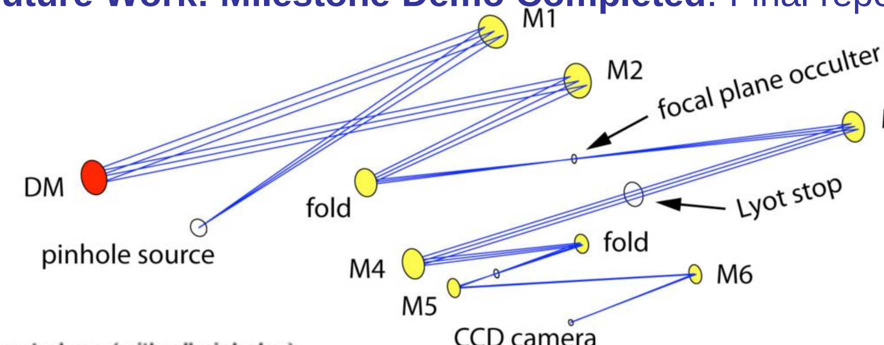
Facility: High Contrast Imaging Testbed 1, JPL.

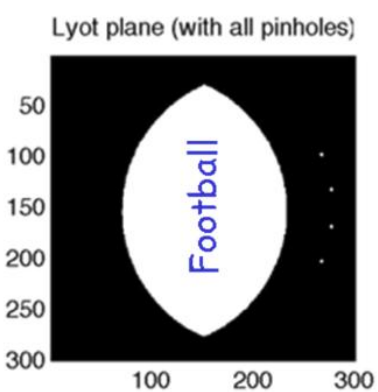
Current Status: ≤10^{-8} contrast, 18 % rms difference at 10% BWD.

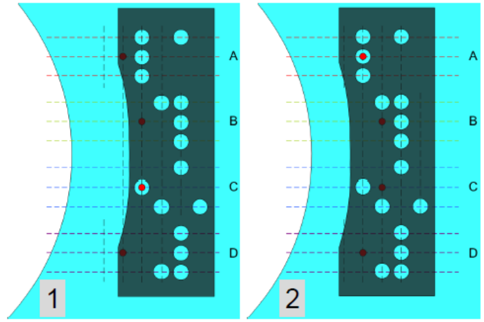
Repeat with incoherent background light

Challenges: Bandwidth sensitivity.

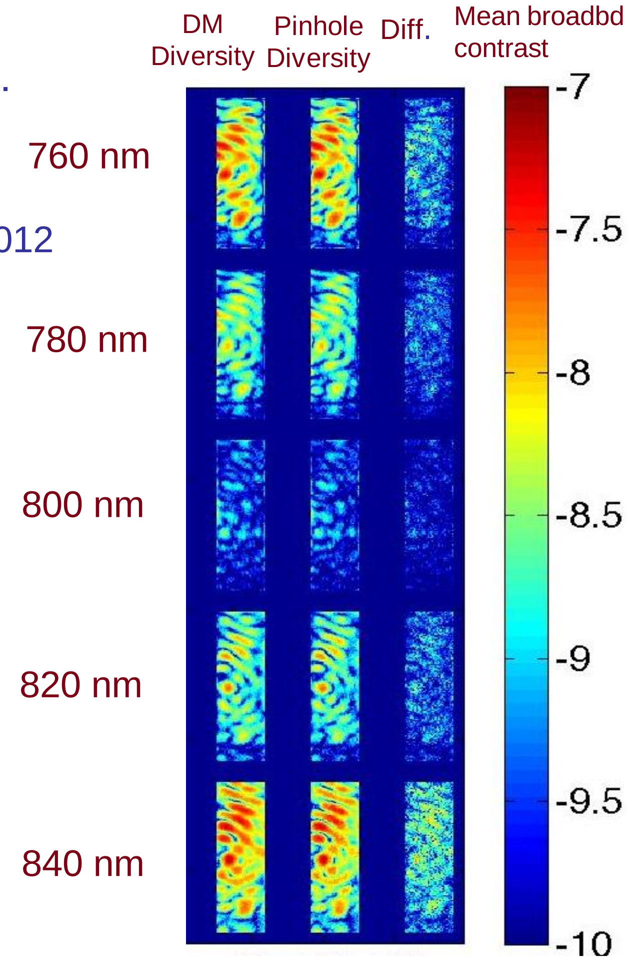
Future Work: Milestone Demo Completed. Final report March 2012







Sliding binary mask



Trauger | Guyon | Krist | Kendrick | Clampin | Kasdin | Figer

Mark Clampin (NASA GSFC)
Visible Nulling Coronagraph

Coronagraph Technology Milestone:
Demonstration of ≤ 10^{-8} monochromatic contrast through visible nulling.

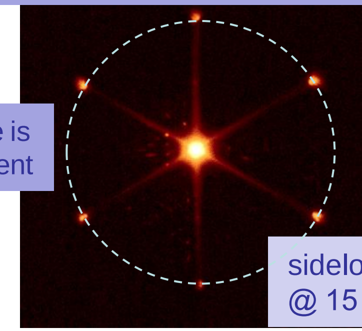
Facility: Visible Nulling Coronagraph Testbed, NASA GSFC.

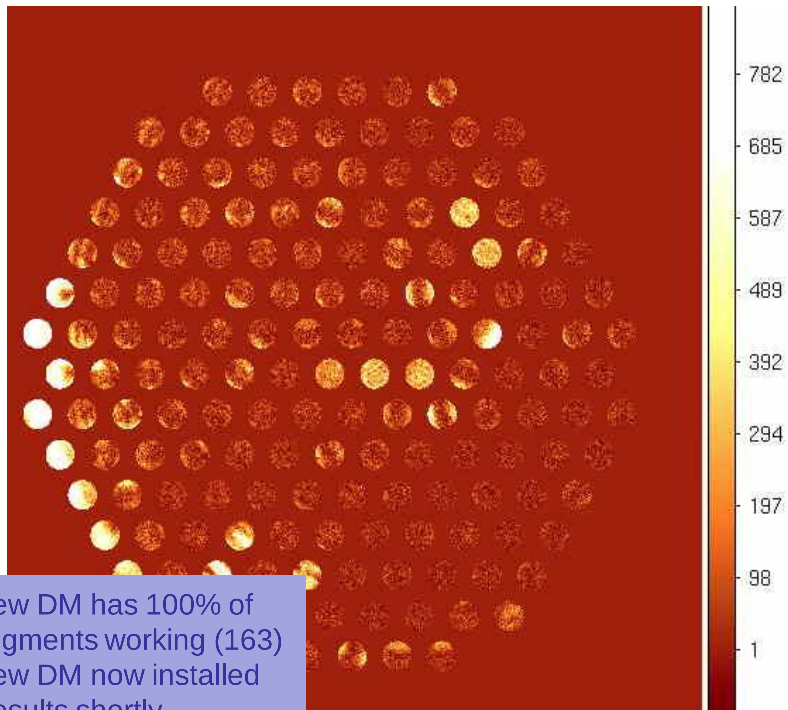
Current Status: 1.5×10^{-6} @ 2λ/D contrast monochromatic. New DM installed in Dec. 2011.

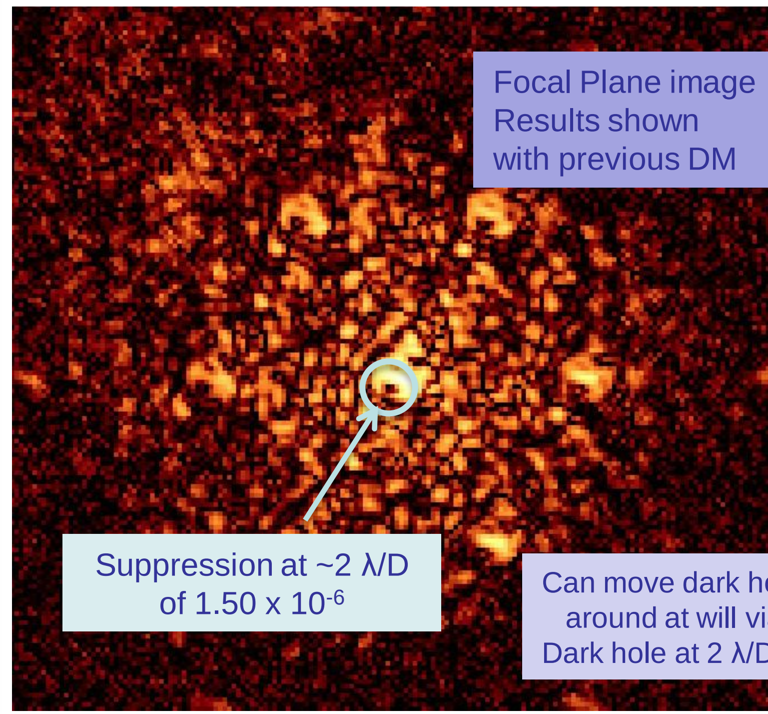
Challenges: State of the art in segmented DMs.

Future Work: Complete milestone in 2012, follow-on with R. Lyon TDEM.

Focal Plane Image thru Spatial Filter Array







Trauger | Guyon | Krist | Kendrick | **Clampin** | Kasdin | Figer

Donald Figer (Rochester Inst. Technology)
A Photon Counting Detector for Exoplanet Missions

Detector Technology Milestone:
Demonstrate the performance of a 256 x 256 zero-read noise (Geiger mode) avalanche photodiode after radiation testing. The device must demonstrate a baseline photon detection sensitivity of at least 35% at 350 nm, 50% at 650 nm, and 15% at 1000 nm.

Facility: MIT Lincoln Laboratory and Rochester Institute of Technology

Current Status: A silicon 256x256 diode array has been bonded to a Read Out Integrated Circuit; the array has been hybridized and tested; a first light image has been obtained with good response in the 300–1000 nm range.

Challenges: Scaling to larger number of pixels (1024x1024).
Future Work: Radiation testing in 2012.

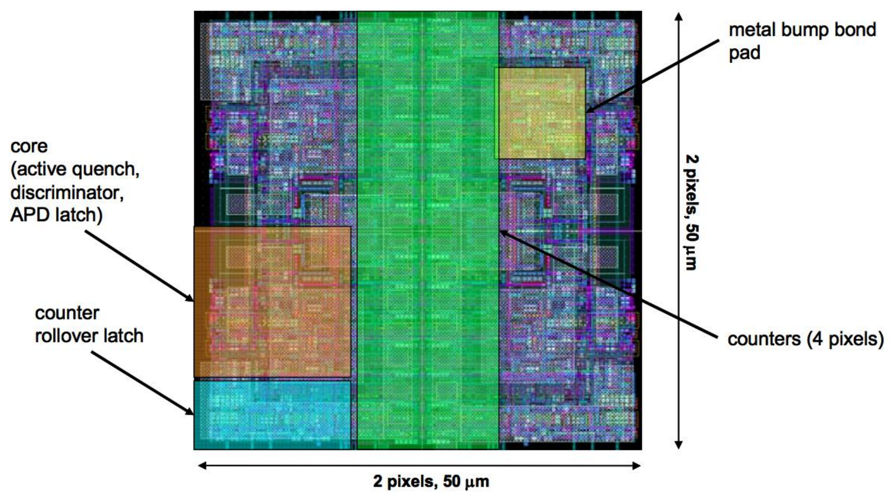


Figure 4. Close-up of the 256×256 ROIC layout, covering a 2×2 pixel area. The counter blocks for all four pixels form a contiguous region. Each pixel has its own isolated core, counter, and bump bond pads, although only one of each is highlighted in this representation.

Trauger | Guyon | Krist | Kendrick | Clampin | Kasdin | **Figer**

Visible Coronagraph Technology Accomplishments: *Modeling and Analysis Infrastructure*

CORONAGRAPH MODELING TOOLS

- **Near-field optical diffraction propagation models w/ broadband optical aberration & wavefront control**
  - Multiple propagation approaches for validation
  - Models for Shaped pupils, Band-limited masks, PIAA
  - Applied to HCIT, TPF-C, ACCESS, PECO
  - Test validation addressed in Technology Milestone #3

CORONAGRAPH ERROR BUDGET TOOL

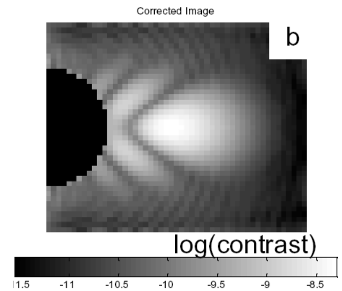
- **Generates top-down error budget of contrast to optical requirements for various Coronagraphs:**
  - Automated Matlab tool w/ Excel front-end, based on optical aberration sensitivities for various coronagraphs
  - Applied to HCIT, TPF-C, ACCESS, PECO, DaVinci

EXTERNAL OCCULTER MODELING TOOL

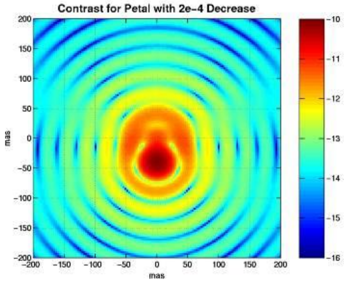
- **Efficient far-field Fresnel propagation algorithms for tolerancing external occulter deployment and stability:**
  - Evaluates contrast degradation as a function of wavelength, inner working angle, petal design & defect
  - Applied NWO, THEIA, & various occulter options
  - Round-robin w/ NGAS, Ball, Princeton to verify results

INTEGRATED MODELING AND ANALYSES

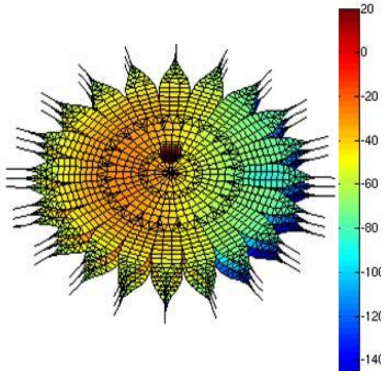
- Integrates thermal/structural/optical/control analyses under one model for high fidelity end-to-end contrast estimates to on-orbit thermal and dynamic perturbations
  - Applied to TPF-C, PECO, THEIA



PIAA residual image after DM correction (Shaklan SPIE 2007)



Contrast degradation due to 1mm width change in a single petal



Temperatures at the front-side of Occulter w/ sun at 5º (20 petals, 54 m tip-to-tip)

REFEREED PUBLICATIONS:

M. Levine and J. Fanson, "*Advanced Thermo-Structural Technologies for the NASA Terrestrial Planet Finder Mission*", **J. of Structural Control** and Health Monitoring, Vol **13**, 1, Jan/Feb 2006, pp. 190-209

S. Shaklan and J. Green, "*Reflectivity and optical surface height requirements in a broadband coronagraph. 1.Contrast floor due to controllable spatial frequencies*" **Applied Optics**, 45 (21) : 5143, 2006

J. Trauger, W. Traub, and HCIT Team, "*A laboratory demonstration of the capability to image an Earth-like extrasolar planet*", **Nature** 446, 771-773 (April 2007)

K. Bala, "*Band-limited image plane masks for the Terrestrial Planet Finder coronagraph: materials and designs for broadband performance*" **Applied Optics**, vol. 47, Issue 2, pp.116-125 (2008)